Evaluation of Terrestrial Laser Scanners for Measuring Vegetation Structure

A comparison of the FARO Focus 3D 120, Leica C10, Leica HDS7000 and Riegl VZ1000

Glenn Newnham¹, John Armston²,³, Jasmine Muir², Nicholas Goodwin², Dan Tindall², Darius Culvenor¹, Pyare Püschel⁴, Mattias Nyström⁵, Kasper Johansen¹

1. CSIRO Land & Water and Sustainable Agriculture Flagship
2. Remote Sensing Centre, Queensland Department of Science, Information Technology, Innovation and the Arts
3. Joint Remote Sensing Research Program, School of Geography, Planning & Environmental Management, University of Queensland
4. University of Trier
5. Swedish University of Agricultural Sciences
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Executive summary

This work has evaluated data acquisition and processing requirements for current commercial time-of-flight and phase-shift terrestrial laser scanners in a forest environment. The instruments in the trial included a FARO Focus 3D 120, Leica C10, Leica HDS7000 and Riegl VZ1000. Scans and supporting standard forest inventory measurements were recorded in the D’Aguilar National Park at a site known as Landers Hut 3 (DSITIA plot code: gold0101) on the 8th and 9th of November 2011.

Key findings from the trial on practical use of commercial scanners for analysis of gap probability include:

- The complete set of measurements required for analysis of gap probability is not directly available from any of the scanners except the Leica C10. In the case of the two phase based instruments (FARO Focus 3D and Leica HDS7000), filtering needs to be performed in order to distinguish gaps in the canopy from multiple beam interceptions, both of which are recorded as no-data under standard processing methodologies. In the case of the Riegl VZ1000, there is no export file format that will maintain links between multiple returns from the one pulse. However, access to the Riegl software development library RiVLib does provide a low-level programmable interface to this required information.
- Hardware and/or software filtering options provided for the phase-shift scanners are sub-optimal for vegetation. Alternative filtering methods were developed that may be improved with further research by including all available information about the point (texture, range, intensity).
- Optimal use of the Riegl instrument would require a tilt mount in order to scan the entire upper hemisphere due to its limited field of view (30 to 130 degrees zenith angle). This tilt mount was not available for the trial and its practical application has not been considered in the analysis.

Conclusions resulting from the comparison of time-of-flight (discrete and multiple return) and phase-shift terrestrial laser scanners for the estimation of digital terrain elevation model (DEM) surfaces, canopy gap fraction and vertical foliage profiles include:

- Pulse density has a negligible impact on return range distributions, DEM surfaces and vertical foliage profiles for all scanners.
- Quality of filtering of data from the phase-shift scanners directly impacts the variance in metrics derived from gap fraction such as leaf area index.
- Sensor parameters such as wavelength and pulse peak energy are important considerations for the phase-shift scanners. The signal-to-noise ratio that can be achieved is highly dependent on levels of ambient radiant flux at the wavelength where the sensor operates. An increase in scan quality (signal integration time) may increase range precision but will also increase exposure to solar radiant flux, thus decreasing the signal-to-noise ratio.
- Time of flight instruments produced smoother and more accurate Digital terrain Elevation Model (DEM) surfaces than the phase based instruments. More sophisticated DEM generation algorithms that are tuned to the radial sampling pattern of terrestrial scanners may improve these results in future.
- Occlusion by near-range terrain and vegetation has a greater impact on DEM error than scanner characteristics or scan settings. Assumption of a planar surface or use of external DEM source may be required for optimal vegetation structure assessment in areas of significant slope or undulating terrain.

In conclusion, time-of-flight instruments are currently providing the best characterisation of vegetation structure, particularly foliage measurements in the upper parts of the canopy, where multiple beam interceptions are not accommodated well by the phase-shift scanners. The development of point filtering and classification algorithms specifically tuned to vegetation assessment may help to address the limitations of single return phase-shift instruments. Although signal-to-noise and ranging artefacts are likely
to continue to be significant challenges, the small differences seen between the Leica phase-shift and time-of-flight instruments are encouraging of the phase-shift approach. If phase-shift scanner specifications continue to progress and data can be improved to the point where it is close to the quality of the time-of-flight instruments then there are distinct advantages of utilising low weight instrument like the FARO Focus 3D. The weight of these instrument leads to easier field deployment and may help to promote greater sampling density. This could be considered an improvement in data quality, since greater sampling density will help to improve understanding of spatial and temporal variance in vegetation structure. Similarly, future improvements in time-of-flight technologies may help to reduce the weight of these instruments making them more practical for field deployment.

The advance in our understanding of differences and limitations of terrestrial laser scanners presented in this work is an important step towards developing operational methods for rapid vegetation structure and biomass assessment. Future work will aim to validate structural variables derived from the four scanners in this study using coincident field measurements. Such investigations will include:

- Development of data filtering and ground return classification algorithms for phase-based data.
- Improved estimation of plant area profiles that account for terrain and clumping.
- The assessment of wood area and volume fractions to allow biomass to be assessed separately for woody and non-woody components.
- Linking airborne and ground-based estimates of structural measurements for calibration and validation of larger area mapping from lidar.
- Methods for feature extraction in complex mixed-species forest for parameterisation of radar backscatter models (branch angles, stem tapering) and estimation of stem diameter, volume, etc.
- Testing the sensitivity of vegetation structure and biomass estimation algorithms to changes in sensor and scan properties.
# Introduction

## 1.1 Background

Broad scale assessments of vegetation structure and above-ground biomass are required for reporting of carbon stores and fluxes, and auditing of vegetation restoration to meet biodiversity and habitat value objectives (Lucas et al., 2010). In order to achieve these objectives, rapid and repeatable ground-based measurements are required to increase spatial and temporal sampling of vegetation structure. Often this is achieved through simplified measurement strategies. For example, traditional allometric equations for biomass estimation often rely on Basal Area (BA) as the sole basis for plot based estimates. However, the accuracy of these equations often suffers when they are applied to new species distributions or outside the region in which they were developed (Eamus et al., 2000). Terrestrial Laser Scanning (TLS) presents an opportunity to obtain more detailed structural characterisation of vegetation. This may help to reduce reliance on site and species specific aspects inherent in allometric equations, thus improve assessment and monitoring of vegetation structure and biomass change.

TLS data can be used to estimate the number of trees per hectare and the distribution of stem diameters at breast height as a foundation for assessing BA. It can also be used to estimate tree height distributions, stem form, branching structure and the vertical distribution of foliage cover. Each of these is an important aspect of vegetation structure which may help to improve estimates of above ground biomass. Of these parameters, height distribution and foliage cover are of particular interest as they can be directly linked to data products from airborne and satellite remote sensing instruments, which often form the basis for broad scale mapping initiatives (e.g. Armston et al., 2009).

There are many examples in the literature of the estimation of detailed vegetation structural metrics and the inference of above ground biomass from TLS data (Ni-Meister et al., 2010; Seidel et al., 2011; Yao et al., 2011). However, the scanners used in published studies vary considerably in terms of the basic ranging method employed and instrument specifications. To date, Maas et al. (2008) is the only published work which compared the relative efficacy of multiple TLS instruments for vegetation structure assessment. However, their work is focussed on stem detection and management and does not discuss the use of TLS for crown and foliage analysis.

There are currently three primary ranging technologies being employing in commercial laser scanners:

1. Time-of-flight discrete-return scanners;
2. Continuous wave phase-shift scanners; and
3. Time-of-flight waveform scanners.

Time-of-flight discrete-return scanners emit a pulse of laser energy and use analogue electronics to measure the discrete time-of-flight of a return echo from intercepted targets. Details of the detection systems are often not disclosed but are based on schemes originating in well established radar technologies (Ullrich and Pfennigbauer, 2011). Some instruments allow the detection of multiple returns from a single pulse. However, there is generally some dead time after a return is registered until subsequent returns can be detected, which is related to the outgoing pulse duration. Time-of-flight discrete-return instruments provide high accuracy at large range and resolve gaps well. In ideal situations the effective range can be in the order of kilometres and the pulse frequency
of these instruments is usually around 100 thousand points per second. This category of commercial scanners has seen the most application to vegetation structure measurement (Cote et al., 2009; Watt and Donoghue, 2005).

Phase based scanners employ a constant wave laser with intensity modulated at a series of frequencies. The shifts in phase of the returned modulations are used to determine range. The main benefit of phase based scanners is that they can sample at much higher frequencies than time-of-flight instruments; in the order of 1 million points per second. They are also generally lighter and cheaper than “equivalent” time-of-flight instruments. This comes at the cost of effective range, which is generally limited to less than 100m depending on the laser pulse peak energy, wavelength and target reflectance characteristics. Phased based scanners are also subject to range averaging in cases where a single outgoing pulse is intercepted by multiple targets along the beam line. This can make the data noisy around the edges of objects, where a trail of points can join a closer object to a partially obscured second objects at larger range. The ambiguity of phase based scanning also means that gaps are more difficult to resolve. For example shots into a clear beam path will result in random ranges being returned. This is generally addressed in firmware or through post-processing, with points removed based on the smoothness, or range texture with respect to neighbouring shots. There are numerous published studies of phase-shift scanners being applied to measurement of canopy parameters (Antonarakis, 2011; Balduzzi et al., 2011; Park et al., 2010) and the assessment of woody vegetation components (Bienert et al., 2007; Liang et al., 2008; Park et al., 2010).

Time-of-flight waveform scanners record the full time trace of energy that is returned after a laser pulse has been emitted from the instrument. This time trace of returned energy is referred to as the waveform. Ranges can be resolved from the waveform by post-processing in much the same way as time-of-flight discrete-return instruments. The key difference is that in the case of full waveform instruments, the full intensity trace is recorded for future analysis, albeit with some range bin discretization, rather than resolving range by proprietary analogue electronic techniques. This is important when the scanner is being employed in very complex media, where the objects being detected are small and distributed in an irregular way in space. Applications include profiling of the atmosphere, bathymetry and sometimes in vegetation canopies. Examples of time-of-flight waveform scanners include the CSIRO ECHIDNA research instrument (Jupp et al., 2008; Lovell et al., 2011) and the commercially available Riegl scanners (Maas et al., 2008; Watt and Donoghue, 2005).

As a means of determining the most appropriate instrument specifications for routine vegetation structural assessment and biomass estimation, we evaluated a number of commercially available TLS instruments in a trial at D’Aguilar National Park on the 8th and 9th of November 2011. Specifically, the objectives of the trial were to:

1. Evaluate field operation, data acquisition and processing requirements for current commercial time-of-flight and phase-shift terrestrial laser scanners in a forest environment; and

2. Compare the value of time-of-flight (discrete-return, waveform) and phase-shift terrestrial laser scanner data for the estimation of gap fraction and apparent foliage profiles.

1.2 Scanner Selection

Two time-of-flight and two phase-shift commercially available TLS instruments were selected for comparison. The FARO instrument was supplied and operated by Laser and Survey Solutions staff on Tuesday the 8th of November 2011. The Riegl and two Leica instruments were provided and operated by CR Kennedy Pty Ltd staff on Wednesday the 9th of November 2011. Instrument specifications are shown in Table 1.

Operation of modern commercial laser scanners is becoming increasingly simplified. All of the scanners tested included touch screen operation with intuitive interfaces. Setup is simplified by inbuilt inclinometers which can compensate for small errors in levelling. The Riegl and both Leica instrument are mounted on survey grade
tripods which provide a very stable platform for operation but weigh approximately 7kg. The FARO instrument was provided with a compact and light weight tripod which was less sturdy but weighs only 2.4kg. With the light weight of the FARO instrument, the tripod did not appear to be unstable during operation but is likely to be less robust.

Instrument settings were varied for each scanner to determine if pulse angular density and integration time had a significant impact on the apparent vegetation structure. An attempt was made to trial equivalent settings for each instrument. However, due to very different instruments designs and terminology used by each manufacturer, best approximations at equivalent settings were adopted. A summary of instrument settings is shown in Appendix A.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Riegl VZ1000</th>
<th>Leica C10</th>
<th>Leica HDS7000</th>
<th>Faro Focus 3D 120</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ranging method</td>
<td>Time-of-flight</td>
<td>Time-of-flight</td>
<td>Phase</td>
<td>Phase</td>
</tr>
<tr>
<td>Returns</td>
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<td>single</td>
<td>single</td>
<td>single</td>
</tr>
<tr>
<td>Wavelength</td>
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<td>532nm</td>
<td>1500nm</td>
<td>905nm</td>
</tr>
<tr>
<td>Max Zenith Range</td>
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<td>320</td>
<td>320</td>
</tr>
<tr>
<td>Laser Class</td>
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<td>3R</td>
<td>1</td>
<td>3R</td>
</tr>
<tr>
<td>Range</td>
<td>1.5-1400m</td>
<td>0.1-300m</td>
<td>0.3-187m</td>
<td>0.6-120m</td>
</tr>
<tr>
<td>600m@20%</td>
<td>134m@18%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Samples/sec</td>
<td>122000</td>
<td>50000</td>
<td>1016000</td>
<td>976000</td>
</tr>
<tr>
<td>Beam divergence</td>
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<td>0.1 mrad</td>
<td>&lt; 0.3 mrad</td>
<td>0.16 mrad</td>
</tr>
<tr>
<td>Scan Configuration</td>
<td>30-130 zenith</td>
<td>Hemispherical</td>
<td>Hemispherical</td>
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<tr>
<td>Colour</td>
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<td>integrated</td>
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<td>integrated</td>
</tr>
<tr>
<td>Weight</td>
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<td>10kg</td>
<td>5kg</td>
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<tr>
<td>Temp Range</td>
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<td>0-40°C</td>
<td>0-45°C</td>
<td>5-40°C</td>
</tr>
<tr>
<td>Approximate Price (AUD, Nov 2011)</td>
<td>$192,250</td>
<td>$149,000</td>
<td>$138,700</td>
<td>$70,000</td>
</tr>
</tbody>
</table>

It should be noted that in standard scanning mode the Riegl VZ1000 does not collect data above 30 degrees zenith. However, it is possible to simulate a full hemispherical scan by recording a second scan with the instrument tilted at 90 degrees from the vertical and then stitching the two scans together. This requires a custom made Riegl tilt mount, which was not available for the trial. As such, unlike the other full hemispherical scanning TLS instruments in the trial, all results reported here for the Riegl instrument use data only from 30 to 130 degrees zenith.
2 Study Site and Sampling Design

2.1 Site Description

The D’Aguilar National Park covers an area of 36,000 ha to the north-west of Brisbane city centre. The park is dominated by eucalyptus woodland with pockets of subtropical rainforest. The TLS trial was conducted at a Queensland Department of Science, Information Technology, Innovation and the Arts (DSITIA) long term monitoring site known as “Landers Hut 3” (see Figure 1) at latitude 27.429S and longitude 152.827E (DSITIA plot code: gold0101). The site is a eucalyptus forest stand with high grass cover, fine litter and woody debris present. Although some large stems have been removed in past logging, the site includes many mature trees with heights ranging up to 35m (see Figure 2).

Figure 1: Location of the TLS trial site (Landers Hut 3, DSITIA code: gold0101) in D’Aguilar National Park to the north-west of Brisbane.
Figure 2: Photos showing vegetation at the TLS trial site (Landers Hut 3, DSITIA code: gold0101) a) upward looking hemispherical photo and b) site photo January 2009

The plot dimensions are nominally 100m by 100m, within which two locations were used as the scan centres (Figure 3), referred to throughout this document as “North” and “South”. These points were marked with stakes and each scanner was positioned directly above each of these points during scanning. Instrument height for each setup varied and was recorded during the trial.

Figure 3: Dimensions of Landers Hut 3 plot (DSITIA code: gold0101) showing the location of the North and South points where TLS scans were recorded, location of Hemispherical Photos (HP), LAI2200 measurement locations, and the area in which stem measurements were recorded.
2.2 Field Measurements

The locations of all tree stems with a Diameter at Breast Height (DBH) greater than 10cm were recorded within a 50m wide strip running down the centre of the plot from its northern to southern extent (see Figure 3). For each tree recorded in the stem map, the following manual measurements were also collected:

- Stem diameter at 0.3m and 1.3m (DBH) (stem diameter tapes);
- Tree top height (vertex hypsometer);
- Crown dimensions (tape and vertex hypsometer); and
- Crown porosity (using plane photography).

Hemispherical photographs and Licor LAI2200 measurements were taken at 2 hourly intervals (from dawn until dusk) on the first day of scanning (8th of November). These measurements were recorded at the TLS scan locations and at three additional points within the plot (see Figure 3). Two camera systems were used for the hemispherical photography:

1. Nikon D300 camera with an 4.5mm hemispherical lens and an F-stop of 5; and
2. Canon EOS 300D camera with an 8mm hemispherical lens, automatic exposure and an F-stop of 5.

See Pueschel et al. (2011) for details of the analyses of these data.

3 Data Pre-Processing

3.1 Proprietary Software and Data Export

Each of the manufacturers of TLS scanners used in the trial has their own proprietary data processing software system (Riegl RiScan Pro, Leica Cyclone, FARO Scene). These software systems are focused on built structure surveys and are not specifically designed for vegetation analysis. All include facility for data viewing, filtering of points, cropping of the point cloud to specific features and exporting Cartesian point coordinates in text and binary formats. The most important feature for vegetation analysis is the ability to export the data in a format that can be easily interpreted and incorporated into other dedicated software systems. The vegetation structure analysis in this study requires the spherical geometry of the scan. This includes the zenith and azimuth angles for each pulse and range for each return.

For the FARO and Leica scanners, data were exported to PTX, which is an ASCII format originally developed by Leica. This format orders the Cartesian points according to vertical scan number and shot number within each scan. It includes records for pulses with no return (i.e. canopy gaps) which are assigned zero range and are important for assessing tree and foliage density. Cartesian coordinates can be converted to spherical (range, zenith and azimuth angles) coordinates based on a zero origin for the TLS instrument. Azimuth and zenith angles for gaps (zero range) can be interpolated based on their scan line and column position.

As the Riegl VZ1000 was the only instrument in the trial to record multiple returns per pulse, the challenge was to find a format that could maintain the association between these multiple returns and a single pulse zenith and azimuth. This is possible using Version 1.4 of the Common lidar Data Exchange Format, known as LAS (see Samberg, 2007). However, the export to LAS in RiScan does not adequately populate the LAS fields to allow associations to be maintained. Additional limitations of the Riegl ASCII and LAS export formats include:
1. There was no information for pulses that had no return (i.e. canopy gaps);
2. Small fluctuations of rotation speed and laser pulse rate resulted in an irregular scan pattern and prevented the data being sorted into scan order;
3. The origin of the sensor coordinate system is different to the laser pulse origin. This resulted in different zenith and azimuth angles recorded for returns from the same pulse, particularly at near range.

Therefore low-level programmable access to the raw binary files generated from a scan was required for this work. Pulse data equivalent to that provided by the FARO and Leica scanners were exported using C++ code incorporating the Riegl C++ RiVLib library, freely available to registered Riegl instrument owners at http://www.riegl.com.

Example range images for each of the scanners are shown in Figure 4. The start azimuth is different for each scan causing a shift in the horizontal axis. The restricted zenith limits for the Riegl data should be noted in Figure 4a, due to the lack of availability of an instrument tilt mount for the trial. There is also a distinct difference in the way gaps are recorded by the time-of-flight Riegl VZ and Leica C10 instruments (Figure 4a and b) when compared to the phase based Leica HDS and FARO Focus (Figure 4c and d). For time of flight instrument there is generally no data recorded within gaps and the range is set to zero, while for the phase based instruments, gaps cause an ambiguous signal which is set to the most likely range. These gaps need to be established through post processing. Methods of filtering phase based data are discussed in the next section.
Figure 4: Range images for each of the TLS instruments a) Riegl VZ1000 (first return range), b) Leica C10, c) Leica HDS7000 and d) FARO Focus 3D 120.
3.2 Filtering Phased Based Data

Phase based scanners are subject to range averaging when the beam intercepts multiple objects. They also return random ranges in canopy gaps due to sky and direct solar radiation. In traditional applications of TLS, these two cases are dealt with in the same way: by removing the points from the point cloud. In vegetation structural analysis, these two cases need to be dealt with differently, since the removal of points that indicate multiple hits would overly inflate gap probability estimates and consequently decrease apparent stem size, cover and Leaf Area Index (LAI) statistics. Sky points on the other hand need to be removed reliably so that true gaps can be identified.

The FARO Scene and Leica Cyclone software include a number of filters to deal with what might ordinarily be considered spurious points in their phase based scanner data. Both include simple threshold filters for range and intensity. In addition they have also implemented similar textural filters that specify the minimum proportion of neighbouring points that must fall within a given distance from each point. For the HDS7000 the default is to apply intensity and range thresholds, as well as range textural filtering on import of the data into Cyclone. For the FARO Focus 3D, two filters are applied in hardware which are described as “clear sky” and “clear contour”. These default filtering methods were found to be non-ideal for the D’Aguilar National Park data. For the HDS7000, default software filtering is too severe, removing sky points but also edges of trunks and branches, as well as clumps of foliage (Figure 5b). For the FARO Focus 3D, hardware filtering only appears to detect large gaps in the canopy, while spurious ranges are still reported in smaller gaps (Figure 5e). Both of these issues can be addressed in software with the application of other software filtering methods. However, to ensure fair comparison between the data we implemented a range based kernel filter to allow consistent batch processing of all phase based data. This filter removed a point if more than 20% of the neighbouring points were separated by greater than 1m in range. The kernel size used for the processing was a 5 by 5 pulse window. Results from this custom filtering are shown in Figure 5c and f.

![Image](a.png) ![Image](b.png) ![Image](c.png)
![Image](d.png) ![Image](e.png) ![Image](f.png)

Figure 5: Leica HDS7000 data: a) prior to filtering; b) after default filtering using the Leica Cyclone software; and c) filtered using the range kernel method; FARO Focus 3D data d) prior to filtering; e) after default hardware filtering; and f) filtered using the range kernel method.
3.3 DEM Generation

Access to terrain height information is important for TLS data processing as it allows vegetation structure to be analysed in terms of height relative to the ground surface, rather than relative to the origin of the sensor coordinate system. In the case of flat terrain this may be as simple as adding the height of the instrument optical centre to the vertical (Z) coordinate in the data. In more complex terrain access to a DEM is required. There are many possible sources for these data but in the ideal case an accurate DEM would be generated from the TLS data itself. However, TLS does not provide the ideal perspective from which to record points on the ground surface, as occlusion by vegetation, ground cover, woody debris and the topography itself increases with horizontal distance from the scanning position.

The derivation of a DEM from each scan was tested using an adaptation of the Zhang et al. (2003) method, which was originally developed for filtering airborne lidar data. Minimum elevation points within 1m by 1m pixels were located and the progressive morphological filter applied to these points to determine ground returns. The thresholds used are shown in Table 2 and were determined subjectively.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B_{\text{start}} ) (m)</td>
<td>1.0</td>
<td>Starting block size for morphological operations</td>
</tr>
<tr>
<td>( B_{\text{max}} ) (m)</td>
<td>9.0</td>
<td>Maximum block size for morphological operations</td>
</tr>
<tr>
<td>Cell size (m)</td>
<td>3.0</td>
<td>Resolution of the minimum elevation raster created for filtering</td>
</tr>
<tr>
<td>( dH_0 ) (m)</td>
<td>0.5</td>
<td>Initial elevation difference threshold.</td>
</tr>
<tr>
<td>Slope</td>
<td>0.2</td>
<td>Factor to adjust elevation difference threshold to account for terrain slope.</td>
</tr>
<tr>
<td>Residual threshold (m)</td>
<td>0.15</td>
<td>Points not included in the minimum elevation raster are classified according to their deviation from the final DEM.</td>
</tr>
</tbody>
</table>

Classified ground returns were then used to generate a continuous DEM at a spatial resolution of 1m using the natural neighbour algorithm. Due to the non-ideal perspective of TLS instruments, DEM radius was restricted to 100m from the scan locations. Height above ground was calculated for each TLS point by subtracting the respective DEM elevation from the point elevation.

Each DEM was validated using an equivalent DEM generated using Airborne Laser Scanning (ALS). This dataset was acquired in 2009 by AAM Hatch with the Leica ALS50-II sensor with a flying elevation of 1800 m, and recording at a maximum scan angle of 18 degrees off nadir. Pulse repetition frequency of 126.2 kHz produced an average pulse density of 2.8 m\(^{-2}\) pulses. The airborne DEM used only returns classified as ground points by the contractor. To be consistent with the TLS data, the airborne DEM was produced at a spatial resolution of 1 m using the natural neighbour algorithm.
3.4 Vertical Foliage Profiles

Vertical profiles of the plant area per unit volume, referred to as foliage profiles, can be calculated using the recorded heights in a point cloud. As a means of accounting for possible variations in the projection of plant area, gap probability ($P_{gap}$) was measured within discrete zenith angle bands. For the case of discrete single return instruments $P_{gap}$ can be approximated by:

$$P_{gap}(z, \theta) = \frac{\#z_i(\theta) \mid z_i < z}{N(\theta)}$$

where the numerator refers to the number of returns that are below a height $z$ relative to the scanner and the denominator is the total number of laser shots in the finite zenith range centred on $\theta$. In the case of a multiple-return instrument like the Riegl VZ1000, we might assume that for a laser shot returning $n_s$ ranges, each range equates to an interception of $1/ n_s$ fraction of the beam area. In this case the equation for $P_{gap}$ becomes:

$$P_{gap}(z, \theta) = \frac{\sum w_i(z_i < z, \theta)}{N(\theta)} \quad \text{where} \quad w=1/n_s$$

Knowledge of $P_{gap}$ allows the calculation of the well known biophysical variable, leaf area index (LAI) as a cumulative profile from ground level to a height $z$ using the equation:

$$P_{gap}(z, \theta) = e^{-G(\theta) \times \text{LAI}(z) / \cos(\theta)}$$

where LAI($z$) is the best estimate based on measurements of $P_{gap}(z, \theta)$ from multiple zenith rings. There is no separation of foliage and woody vegetation in this work, so we assume plant area index is equal to LAI. The projection of the vegetation elements is described by the Ross (1981) $G(\theta)$ function. One simple formulation of $G(\theta)$ is described by Jupp et al (2008), where the projection of vegetation elements is separated into their horizontally and vertically projected components:

$$G_h(\theta) = \cos(\theta) \quad \text{and} \quad G_v(\theta) = 2 \times \sin(\theta) / \pi$$

This allows the linear estimation of LAI, as the sum of the horizontal ($\text{LAI}_h$) and vertical ($\text{LAI}_v$) components using the equation:

$$- \log(P_{gap}(z, \theta)) \times \cos(\theta) = \text{LAI}_h(z) + \text{LAI}_v(z) \times 2 \times \tan(\theta) / \pi$$

The mean projection angle, sometimes referred to as the mean leaf angle (MLA), can also be derived as follows:

$$\text{MLA}(z) = \arctan(\text{LAI}_v / \text{LAI}_h)$$

and a foliage profile, sometimes referred to as the foliage area volume density (FAVD) can be calculated using the derivative of LAI such that:

$$\text{FAVD}(z) = \delta\text{LAI}/\delta z$$

In steeply sloping or undulating terrain, profiles which use a height relative to the instrument may be significantly distorted. In such a case, $z$, are substituted by $z_{dem,i}$ in the calculation of $P_{gap}$, where $z_{dem,i}$ is the height of a TLS return relative to the scanner minus the ground surface height relative to the scanner at the planimetric location $i$. 


4 Data Analysis and Evaluation

Analysis of the TLS data included qualitative assessments of the point clouds, assessing variations in range distributions between scanners, as well as variation between scans from the same instrument using different scanner settings. Simple structural variables were also derived and compared. These do not represent an exhaustive set of variables that might be extracted from TLS but were selected to highlight specific variations between the datasets.

4.1 Point Cloud Artefacts

Examples of the unfiltered point clouds for each of the four scanners are shown in Figure 6, where they have captured points from two tree trunks at approximately 9m horizontal range from the instrument. The two phase based scanners (FARO Focus and Leica HDS) show a scatter of points that fall between the two trunks where both trunks have intercepted a single pulse (Figure 6 a and b). These points need to be considered in the analysis of gap probability statistics (foliage cover, LAI and in the horizontal plane, BA), since they represent true interceptions of the beam by vegetation. However, these points should be removed for the purpose of structural analysis (e.g. the analysis of single stem form).

The Riegl scanner shows a similar range averaging effect between the two trunks. However, this is likely due to the default waveform processing algorithm, which is unable to separate overlapping returns if they are separated by less than 0.8m in range (see RIEGL_VZ-400_News_03-2009.pdf). Since these points represent true interceptions of the beam, they need to be considered for the purpose of cover statistics. The Riegl output data file provides a measure of deviation in shape from the transmitted pulse that can be used to remove these returns if detailed structural analysis is required.

The Leica C10 data has no visible range averaging effects between overlapping features. Given that multiple returns are likely to still be occurring, the proprietary algorithm is likely to be recording the first return above a given return intensity threshold or a single range to the highest intensity return. This ranging algorithm is fixed in hardware and its details are not available to the user.
4.2 Range Summaries

The range distribution for points recorded by each scanner is shown in Figure 7. In the case of the FARO Focus 3D and Leica HDS7000, ranges shown in the figure have been filtered as described in Section 3.2. The figures represent a probability density function where the number of ranges returned within 1 metre increments from the instrument is normalised by the total number of shots in the scan. The impact of different scanner settings can be seen in the Figure 7. The FARO Focus 3D showed a significant difference in range distributions, with the medium resolution, high quality (signal integration time) scans returning substantially fewer ranges that could be associated with vegetation components, when compared to the lower quality scans. This may be associated with an increase in ambient light interference with increasing integration time. The other three scanners showed very consistent distributions of returned range for all scanner settings.
Figure 7: The distribution of ranges returned by each TLS instrument for both the North and South sub-plots at Landers Ht 3. The legend for each plot indicates scanners resolution and phase based quality settings. Plots for the Riegl VZ1000 data are only first returns recorded by the instrument.
Range distributions are heavily skewed toward smaller values. This is due to near field objects that intercept the beam and obscure objects in the far field. Within a forest (or any medium) of randomly distributed vegetation components the expected distribution of returned ranges is an exponential curve. Deviation from this exponential decay is due to both the many return ranges from the ground surface in the lower hemisphere of the scan and the clumping of vegetation components into discrete trees.

Unlike the other instruments in the trial, which only record a single return per outgoing pulse, the Riegl VZ1000 records a maximum of four returns per pulse (as imposed by Riegl waveform processing). Multiple ranges are only returned when the beam is partially intercepted by more than one object. For example when an outgoing beam hits the edge of one tree and the non-intercepted portion of the beam continues on to be intercepted by a tree at a greater range. There is a finite range limit within which the default Riegl ranging algorithms do not distinguish between multiple interceptions and an average range is recorded (see Figure 6). In these cases there may be possibilities of post-processing waveform data to distinguish these multiple ranges.

The impact of multiple returns on the distribution of range data from the Riegl VZ1000 can be seen in Figure 8. When only first returns are considered, the range distribution has a greater bias toward shorter ranges. With the addition of second returns, a greater number of ranges are recorded across the full distribution. The addition of third and fourth returns has only a small impact and influences the distribution more as ranges increase.

![Figure 8: The distribution of ranges for low resolution Riegl scans, including only first returns, first and second returns, first second and third returns and all four returns. High resolution scans provide a visually indistinguishable result from the low resolution scans.](image)

Variation in the distribution of ranges recorded in medium resolution scans by each of the four instruments is shown in Figure 9. Only the first return ranges for the Riegl VZ1000 are shown. There is a clear similarity in the shape between the distributions for the FARO Focus 3D, Leica HDS7000 and Leica C10. The Leica C10 provides the greatest proportion of longer ranges that are consistent with vegetation components, as opposed to shorter ranges that are more likely to be ground returns. The filtered Leica HDS7000 data provide a very similar distribution, while the FARO Focus 3D provided a lower proportion of returns consistent with vegetation.

The distribution of ranges from the Riegl VZ1000 was significantly different to the other instruments due to the limited zenith angle range, which is between 30 and 130 degrees. The lack of data associated with tree crowns above the instrument has a substantial effect on the range distribution from 10 to 20 metres. Beyond this distance the Riegl records more ranges than the other four instruments, even when only first returns are considered.

20 | Evaluation of Terrestrial Laser Scanners for Measuring Vegetation Structure
4.3 DEM Validation

Digital Elevation Models generated using the procedure described in Section 3.3 are shown in Figure 10. Spurious points can be seen to have a major influence on the FARO Focus 3D and Leica HDS7000 DEMs. It may be possible to remove these artefacts by employing more sophisticated filtering and smoothing methods. In general the Leica C10 and Riegl VZ1000 provided a much smoother surface, without the need for significant filtering.

The difference between each TLS DEM and the airborne lidar DEM were assessed within a horizontal radius of 100 metres from the instrument location. As TLS scans were not registered to map coordinates, each DEM was rotated until a minimum difference was found between the TLS and airborne data. Differences were then summarised as mean deviation within increasing circular areas with radii of 10, 25, 50 and 95 metres (see Table 3). The Leica C10 and Riegl VZ1000 instruments produced the lowest mean deviation, particularly at ranges less than 50m. The FARO Focus 3D produced the largest error relative to the airborne DEM. The hill shade images support these results with the Leica C10 producing a smoother surface which agrees closely with the airborne DEM. The DEM generated using the FARO Focus 3D data showed comparatively high amount of spurious depressions in the surface. A road shown in the south-west corner of the airborne DEM, at a distance greater than 70m from the TLS scan location, is not evident in any of the TLS derived DEM surfaces.
Figure 10: Example DEM surfaces for the south sub-plot a) airborne Leica ALS50-II  b) Leica C10, c) FARO Focus 3D, d) Leica HDS7000 and e) Riegl VZ1000. Note: Hill shading was created with a 45 degree solar elevation and 45 degree solar azimuth.

Table 3: Average difference between airborne and terrestrial lidar based DEM relative to the distance from scan centre.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Location</th>
<th>Resolution</th>
<th>10</th>
<th>25</th>
<th>50</th>
<th>75</th>
<th>95</th>
</tr>
</thead>
<tbody>
<tr>
<td>C10</td>
<td>North</td>
<td>High</td>
<td>0.284</td>
<td>0.982</td>
<td>2.180</td>
<td>3.606</td>
<td>3.671</td>
</tr>
<tr>
<td>C10</td>
<td>North</td>
<td>Low</td>
<td>0.303</td>
<td>1.017</td>
<td>2.248</td>
<td>3.595</td>
<td>3.399</td>
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<tr>
<td>C10</td>
<td>South</td>
<td>High</td>
<td>0.119</td>
<td>0.353</td>
<td>0.914</td>
<td>3.663</td>
<td>3.56</td>
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<tr>
<td>C10</td>
<td>South</td>
<td>Low</td>
<td>0.163</td>
<td>0.389</td>
<td>0.991</td>
<td>3.506</td>
<td>3.411</td>
</tr>
<tr>
<td>Faro</td>
<td>North</td>
<td>Low</td>
<td>1.118</td>
<td>0.961</td>
<td>2.274</td>
<td>4.269</td>
<td>4.126</td>
</tr>
<tr>
<td>Faro</td>
<td>South</td>
<td>Low</td>
<td>1.226</td>
<td>0.791</td>
<td>1.385</td>
<td>2.713</td>
<td>2.602</td>
</tr>
<tr>
<td>HDS7000</td>
<td>North</td>
<td>High</td>
<td>3.209</td>
<td>1.928</td>
<td>2.635</td>
<td>4.403</td>
<td>4.951</td>
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<tr>
<td>HDS7000</td>
<td>North</td>
<td>Low</td>
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<td>1.183</td>
<td>2.667</td>
<td>4.49</td>
<td>4.193</td>
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<td>HDS7000</td>
<td>South</td>
<td>High</td>
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<td>0.791</td>
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<td>2.788</td>
<td>3.388</td>
</tr>
<tr>
<td>HDS7000</td>
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<td>1.205</td>
<td>3.134</td>
<td>3.273</td>
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<tr>
<td>Riegl</td>
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<td>High</td>
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<td>2.460</td>
<td>3.511</td>
<td>3.183</td>
</tr>
<tr>
<td>Riegl</td>
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<td>Low</td>
<td>0.456</td>
<td>1.287</td>
<td>2.642</td>
<td>3.759</td>
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<tr>
<td>Riegl</td>
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<td>0.294</td>
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<td>1.784</td>
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<tr>
<td>Riegl</td>
<td>South</td>
<td>Low</td>
<td>0.124</td>
<td>0.324</td>
<td>1.003</td>
<td>2.161</td>
<td>2.124</td>
</tr>
<tr>
<td>Combined</td>
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<td></td>
<td>0.761</td>
<td>0.848</td>
<td>1.754</td>
<td>3.393</td>
<td>3.361</td>
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</table>
The comparison of DEM surfaces also revealed different error characteristics between the north and south sub-plots (Table 2). The DEM profiles show a high level of agreement at the south sub-plot out to 50-75m from the sensor (Figure 11). In contrast, a systematic bias is evident at the north sub-plot, with the positive bias in the TLS DEM elevations increasing with range.

![Figure 11](image1.png)

**Figure 11:** Comparison of Airborne and TLS DEM profiles with distance from scan location for the a) south sub-plot and b) north sub-plot.

The ability of TLS instruments to record a return from the ground surface may have differed between sub-plots due to occlusion by topography and vegetation. This is supported by the distribution of DEM residuals (airborne DEM minus TLS DEM). Errors as high as 8m are evident correspond to depressions in the landscape (Figure 12a and b). Furthermore, a cross-sectional profile shown in Figure 13 shows that there is little evidence of ground returns being returned from horizontal ranges greater than 30m.

![Figure 12](image2.png)

**Figure 12:** DEM residuals for the Leica C10 high resolution scan (airborne elevation minus C10 elevation) for the a) south sub-plot, b) north sub-plot
Figure 13: TLS profile produced using the Leica C10 high resolution scan showing occlusion at distances greater than 25m.

Additional research to optimise the classification of ground returns and provide an adequately smooth surface for the correction of the complete point cloud is important if structure is to be assessed as a function of true height above the ground surface. Although ideally an accurate DEM could be generated from a single TLS scan, other options for correction of the data include access to external data or the derivation of an approximate DEM, such as estimation of a best fit planar surface.

4.4 Foliage Profile Comparison

Although correction of the point cloud to true height above DEM was performed, the phase based FARO Focus 3D and Leica HDS7000 produced spurious artefacts in the DEM, which propagated through to the derived foliage profiles. To assess variation in foliage profiles independent from these artefacts, the uncorrected foliage profiles are presented in Figure 14. These were produced according to the methods described in Section 3.4. The profiles show an estimate of the vegetation area density at any given height based on the proportion of points returned. The profiles for all four instruments show similar features, although their magnitude varies considerably. At the north sub-plot, foliage profiles show a single dominant overstorey peak, while at the south sub-plot the profiles consistently demonstrate three vertical regions of highest plant area density.
In Figure 14, only first returns from the Riegl instrument are considered. Nonetheless, the magnitude of the foliage profiles for the Riegl is greater than the other three instruments in the trial. They also appear to detect greater quantities of vegetation in the upper layers of the canopy, particularly the dominant overstorey peak at 20m height in the South sub-plot. These profiles can be integrated across the vertical dimension to give the LAI estimates shown in Table 4. For the Riegl the LAI was approximately 2.2 for the North sub-plot and 2.0 for the South plot. This contrasts with an LAI of around 2.0 for North and 1.8 for South from the two Leica instruments and only 1.36 and 1.15 for the FARO Focus 3D high resolution scan. The FARO profiles also appear to detect less plant area density in the upper parts of the canopy, which is particularly obvious in the relative reduction in the dominance of the upper peak in the South sub-plot. Although the magnitude in the LAI estimate is quite different between instruments, the relative magnitude of LAI between North and South sub-plots remains relatively stable, varying between 0.85 and 0.91.

Table 4: Leaf area index derived for each TLS scan from vertical integration of the foliage profiles shown in Figure 14. The last column refers to the ratio of the LAI at the South and North sub-plots.

<table>
<thead>
<tr>
<th>Scanner</th>
<th>Resolution</th>
<th>Quality</th>
<th>North LAI</th>
<th>South LAI</th>
<th>LAIs/LAIn</th>
</tr>
</thead>
<tbody>
<tr>
<td>FARO Focus</td>
<td>High</td>
<td>mid</td>
<td>1.36</td>
<td>1.15</td>
<td>0.85</td>
</tr>
<tr>
<td>FARO Focus</td>
<td>Mid</td>
<td>high</td>
<td>0.48</td>
<td>0.43</td>
<td>0.88</td>
</tr>
<tr>
<td>FARO Focus</td>
<td>Mid</td>
<td>mid</td>
<td>1.14</td>
<td>0.98</td>
<td>0.85</td>
</tr>
<tr>
<td>Leica HDS</td>
<td>High</td>
<td>mid</td>
<td>2.02</td>
<td>1.82</td>
<td>0.90</td>
</tr>
<tr>
<td>Leica HDS</td>
<td>Mid</td>
<td>high</td>
<td>1.97</td>
<td>1.81</td>
<td>0.92</td>
</tr>
<tr>
<td>Leica HDS</td>
<td>Mid</td>
<td>mid</td>
<td>1.98</td>
<td>1.81</td>
<td>0.91</td>
</tr>
<tr>
<td>Leica C10</td>
<td>High</td>
<td>NA</td>
<td>1.94</td>
<td>1.70</td>
<td>0.88</td>
</tr>
<tr>
<td>Leica C10</td>
<td>Low</td>
<td>NA</td>
<td>1.97</td>
<td>1.72</td>
<td>0.87</td>
</tr>
<tr>
<td>Riegl VZ</td>
<td>High</td>
<td>NA</td>
<td>2.18</td>
<td>1.99</td>
<td>0.91</td>
</tr>
<tr>
<td>Riegl VZ</td>
<td>Low</td>
<td>NA</td>
<td>2.21</td>
<td>2.01</td>
<td>0.91</td>
</tr>
</tbody>
</table>
Figure 14: Foliage area volume density produced using uncorrected height values (height relative to the instrument) for each of the four instruments both the north and south sub-plots. Riegl profiles shown have included only first returns in the calculation of gap probability.
In the case of the C10 and Riegl, the results produced a predictable vertical compression in the foliage profile as the absolute elevation of vegetation components was reduced to their relative height above the terrain surface. The example shown in Figure 15 indicates a change in the apparent height of the profile in the south plot by approximately 3m, with less effect in the north sub-plot. The distinct peaks that appear in the uncorrected profiles, appear less distinct after DEM correction. This is likely due to the merging of the effect of distinct crowns which may truly be part of the same forest strata.

Figure 15: Foliage area volume density produced using: (a) uncorrected height values (height relative to the instrument); and (b) corrected height values (height relative to the DEM surface) for the C10 instruments at both the north and south sub-plots.
5 Discussion and Future Research

The objective of this work was to demonstrate differences in the data recorded by current commercial Terrestrial Laser Scanners (TLS) when operated in a forest environment. The instruments included two scanners that use phase-shift ranging and two that use a time-of-flight ranging method, which is more conventional in TLS for deriving vegetation structural parameters. All four instruments were found to be practical during field operation and could all provide a basis for structural assessment of the D’Aguilar National Park forest stand. However, there are clear distinctions in the processing requirements and data characteristics of the instruments, when used in a forest environment in which irregularly shaped and distributed targets (i.e. tree leaves, grass, etc) make up a large proportion of the intercepted material.

Although phase-shift scanners provide the benefits of low instrument weight and high speed scanning, adequate processing of these data for vegetation structural characterisation requires filtering of the point cloud. This filtering needs to be performed in such a way as to identify the difference between non-interceptions (within canopy gaps) and partial beam interceptions (at the edge of canopy components). Default filtering for the Leica HDS and FARO Focus 3D does not appear to be immediately adequate for achieving this objective. The customised filtering applied in this study did provide adequate results but requires further research to incorporate additional attributes of the point cloud and to determine the impact of scanner parameters such as laser wavelength, pulse intensity and return signal integration time.

Each TLS dataset provides a very detailed record of vegetation structure at a given point in space and time. Each scanner evaluated has a dedicated data processing software package which is adequate for point cloud interrogation and manual extraction of basic structural variables at the single tree level. However, manual interrogation of digital point clouds is labour intensive and may be subject to operator subjectivity. Automated methods for extraction of key vegetation structural variables are required if the technology is to be incorporated into state and national natural resource reporting frameworks. For this reason, this study has focused on automated extraction of terrain elevation and vertical profiles of vegetation density. With further research it is anticipated that more complex structural variables could be extracted using automated routines.

Access to an accurate Digital terrain Elevation Model (DEM) is an important consideration in assessing vegetation structure as a function of height. Ideally a DEM could be extracted directly from the TLS scan to remove the need for using an external source (e.g. airborne laser scanning data). The DEM surfaces generated using the phase-shift scanners were subject to spurious low points which precluded their use in the correction of vegetation density profiles. Very little impact of pulse (angular sampling) density was seen in the DEM surfaces. The time-of-flight instruments produced smoother DEM surfaces, although their accuracy decreased with distance from the instrument. This is primarily due to occlusion of the ground surface by ground layer vegetation, woody debris and the terrain. Such errors may be very low for a flat un-vegetated site but are likely to increase for a site with complex terrain with dense vegetation cover in the understory and/or overstorey. The implementation of DEM algorithms that are specifically tuned to the radial sampling pattern of TLS are likely to go some way to addressing these deficiencies, and increasing the range to which reliable DEMs can be generated. However, in some cases it may be adequate, and in certain situations more accurate, to assume a planar surface out to a pre-specified range.

Vegetation density profiles produced using each of the four instruments showed similar vertical structure and were insensitive to pulse density. However their magnitude, as characterised by Leaf Area Index (LAI), varied. This was particularly true for the FARO Focus 3D, where the leaf area estimate was much lower than the other instruments and impacted by the quality setting (integration time) of the instrument. The impact of data filtering parameters on the phased-shift scanner profiles was not assessed but is likely to be significant. The highest LAI
was recorded by the Riegl VZ1000, which also recorded a greater proportion of returns at larger distances from
the instrument, even when considering only the first range for each outgoing pulse. Interestingly the ratio of LAI
between the two sub-plots was very consistent between instruments and scan settings. However this result needs
to be replicated at a greater number of sites. Given a stable relative measurement, it may be possible to use
cheaper phase-based scanners if a calibration to absolute LAI can be established.

There is a clear distinction between the instruments tested in their practical application to the analysis of
vegetation structure. The two time-of-flight scanners provide immediate utility in the assessment of vegetation
structure. Gaps in the canopy can be easily identified in the data and multiple beam interceptions are dealt with
in a consistent way, by either ignoring successive returns in the case of the Leica C10, or by recording up to four
returns from the same pulse in the case of the Riegl VZ1000. In contrast, the two phase-shift scanners required
customised filtering in an attempt to remove returns in canopy gaps while maintaining returns for partial
vegetation hits. The filtering implemented for this report can be improved with further research and the
limitations of the current approach have had some effect on the assessments of vegetation structure. However,
these instruments had a shorter range, as indicated by their distribution of returned ranges, while vertical profiles
were biased toward the bottom of the canopy and reported less plant area index as a whole.

Although the time-of-flight scanners provide immediate utility in vegetation structure assessment this comes with
both cost and weight penalty. Phase-shift scanners can currently be purchased for at significantly lower cost than
the time of flight scanners (Table 1). They are also generally lighter, which makes them more practical for field
operation. Given that one of the greatest uncertainties in vegetation assessment is spatial variance, the ability to
record more scans and sample more of the landscape has its own positive impact on data quality. If future
research can overcome some of the limitations of phase-shift scanner data, then these instruments may have a
significant part to play in future vegetation structural assessment.
6 References


### Appendix A: Scan Settings Summary

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<th>ScanNo</th>
<th>Location</th>
<th>File Name</th>
<th>Resolution</th>
<th>Quality</th>
</tr>
</thead>
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<td>0.065 × 0.065</td>
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<td>0.031 × 0.030</td>
</tr>
<tr>
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<td>North</td>
<td>north_high_res_int_rgb</td>
<td>100</td>
<td>0.065 × 0.065</td>
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</table>

<table>
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<tr>
<th>Hardware</th>
<th>Filters</th>
<th>Scan Time</th>
<th>Instrument Height</th>
<th>Comments</th>
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<tr>
<td>Lieca C10</td>
<td></td>
<td>16:00</td>
<td>163</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>4:30</td>
<td>163</td>
<td>Colour</td>
</tr>
</tbody>
</table>

| 5      | North    | DERM gold south1 | mid | normal | 1:40 | 168 |
| 6      | North    | DERM gold south2 | mid | premium | 6:42 | 168 |
| 7      | North    | DERM gold south9 | super high | normal | 6:00 | 168 |

| Leica HDS7000 |         |         |         |         |
|               |         |         |         |         |

| 1      | South    | DERM gold north10 | super high | normal | 1:40 | 166 |
| 2      | South    | DERM gold north11 | mid | normal  | 1:40 | 166 |
| 3      | South    | DERM gold north12 | mid | premium | 6:42 | 166 |

| FARO Focus 3D 120 |         |         |         |         |
|                   |         |         |         |         |

| 1      | South    | Gold0101_25s000 | 0.2x | 4x | 2:03 | 165 |
| 2      | South    | Gold0101_25s001 | 0.2x | 8x | 3:44 | 165 |
| 3      | South    | Gold0101_25s002 | 0.5x | 3x | 16:16 | 165 |
| 4      | South    | Gold0101_25s003 | 0.5x | 3x | 16:16 | 165 |
| 5      | South    | Gold0101_25s004 | 0.2x | 8x | 3:44 | 165 |
| 6      | South    | Gold0101_25s005 | 0.2x | 4x | 2:03 | 165 |

| 7      | North    | Gold0101_25n000 | 0.2x | 4x | 2:03 | 156 |
| 8      | North    | Gold0101_25n001 | 0.2x | 8x | 3:44 | 156 |
| 9      | North    | Gold0101_25n002 | 0.5x | 3x | 16:16 | 156 |
| 10     | North    | Gold0101_25n003 | 0.5x | 3x | 16:16 | 156 |
| 11     | North    | Gold0101_25n004 | 0.2x | 8x | 3:44 | 156 |
| 12     | North    | Gold0101_25n005 | 0.2x | 4x | 2:03 | 156 |

| Riegl VZ1000 |         |         |         |         |
|              |         |         |         |         |

| 1      | South    | rieg|south_low | 0.072 ** | 300 *** | 0:58 | 168 |
| 2      | South    | rieg|south_high| 0.018 | 300 | 0:58 | 168 |
| 3      | North    | rieg|north_low | 0.072 | 300 | 15:12 | 166 |
| 4      | North    | rieg|north_high| 0.018 | 300 | 15:12 | 166 |

* Vertical Resolution × Horizontal Resolution
** Degrees
*** kHz
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