Evaluating the use of Optech's ILRIS-3D LASER imaging system for forest metric assessment in a managed pine plantation and an unmanaged mixed deciduous stand

by

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Contents

List of Figures

List of Tables

Executive Summary

This report details an evaluation of a ground based scanning LiDAR system for forest mensuration data extraction. Two plots were investigated in depth; a red pine conifer plantation and a deciduous stand dominated by sugar maples. LiDAR point cloud data were collected over a six hour period by Optech Incorporated on July 5th 2002 using an ILRIS 3D laser imager, and subsequently analysed in the *Innovmetric* "Polyworks" software suite. Ground truth data were manually collected over several days during the same time period as the LiDAR survey, and entered into a spreadsheet for subsequent comparison. There were more than 130 trees in both plots and the following parameters were investigated:

1. Stem location
2. Stem density
3. Tree height
4. Stem diameter at breast height (DBH)
5. Crown diameter
6. Biomass and timber volume

It was found that all parameters could be measured or estimated using the ILRIS 3D imager. There was a slight systematic under-estimation of mean tree height resulting from canopy shadow effects but there was no systematic bias in ILRIS derived volume estimates, which were within 7% of manually derived estimates for both plots. With further testing of the methodology over different site types, canopy shadow effects could be minimised or empirically compensated for. Parameters 1 to 4 can be measured objectively with potentially little manual intervention. Although, locating and counting trees in the multi-tiered deciduous plot required more subjective interpretation than in the pine plantation. Individual tree crown diameter estimates could not be estimated objectively in this study but it was possible to estimate the overall planimetric canopy gap fraction. However, subjective estimates of crown diameter using ILRIS data are probably at least as good as the equally subjective manual field measurements.

Several challenges were faced in undertaking this study:

1. The ILRIS sensor was not designed with forest biomass data extraction in mind;
2. Due to this being the first survey of its kind, the ILRIS data were not collected optimally for the task at hand;
3. The two-week software license used to evaluate information extraction techniques was highly limiting, and not all data extraction techniques were tested.

There are many modifications that could be made to the sensor and its mounting bracket that would improve its performance for this application area. It is also known that more accurate methods are available within the software tested for the extraction of certain parameters. However, despite these challenges, this study has demonstrated that ILRIS is a powerful tool for forest mensuration data extraction and biomass assessment. As is, the technology already provides a very capable means of forest inventory and biomass assessment, and could at least be used as a supplement to more traditional data collection methodologies. However, with further development of the technology, sampling and data extraction methods, this kind of technology could lead to a paradigm shift in the way we collect forestry and vegetation data.

Preface

The idea of applying ILRIS to forest mensuration applications was crystallized during conversations with CSIRO researchers and Mr. Wayne Szameitat of Optech Incorporated while attending the International Geoscience and Remote Sensing Symposium in Sydney, July 2001. Consequently, this project was initiated by C-CLEAR (the Canadian Consortium for LiDAR Environmental Applications Research) in consultation with Optech in January 2002. Preliminary preparations and GPS survey work were carried out by Otterburn Geographic. The ILRIS 3D survey took place on the 5th of July 2002 as part of a multi-sensor campaign to test ILRIS, ALTM, GPS and POS backpack systems for forest biometric assessments. The author of this report commenced postdoctoral activities with the Laboratory for Remote Sensing of Earth and Environmental Systems, Queen's University at the time of the survey, and this project has been assimilated into the LaRSEES LiDAR forestry research program.

Acknowledgements

Several people assisted with data collection and processing, and the author of this report acknowledges the following people and organisations: Optech Incorporated for providing the ILRIS 3D laser imager and a two-week software license of Polyworks; Applanix for providing the use of and operating their prototype POS LS Backpack inertial surveying equipment to survey in some of the tree stem locations; Cansel for GPS survey support; York Region for allowing us to use the Vivian Forest for this research; Dr. Paul Treitz of the Laboratory for Remote Sensing of Earth and Environmental Systems, Queen's University for loaning some of the mensuration data collection equipment; Mr. Colin Young-Pow and Mr. Brad Ysseldyk for organising, collecting, processing the data, and answering my many questions; Mr. Chris Gynan of Silv-Econ for helping with plot selection; Mr. Steve D'eon of the Canadian Forest Service for assistance with allometric equations; Mr. Ron Chasmer of Reculver Enterprises for assistance in the field; Mr. Enda Keane of Mapex Europe for providing some supplementary test data; Miss Laura Chasmer for collecting and working up much of the ground truth mensuration data used in this report and assisting with analysis.

1 Introduction

The vegetated biomass within many of the World's forest regions is considered of high importance for the wide variety of socio-ecological functions that these areas provide. Two of the most notable functions, given today's global political and economic environment, are perhaps: i) timber as a raw construction material; and ii) the ability for forests to sequester CO_2 from the atmosphere and store it within leafy and woody biomass. The first of these functions drives a multibillion dollar global industry; and the second, leads to the identification of forest areas as potential CO_2 storage "credits", that may soon be traded on global markets and used to offset possible taxes or fines associated with a nation's industrial emissions. In both cases, there is a necessity to be able to measure and monitor forest biomass attributes.

This report presents an evaluation of a relatively new ground based scanning LiDAR system for forest mensuration data collection. The LiDAR survey was conducted by Optech Incorporated on July 5th 2002 using an ILRIS 3D laser imager (described below), and subsequently analysed in the *Innovmetric* "Polyworks" software suite. Ground truth data were manually collected coincident with the LiDAR survey for comparative purposes. There are six sections (and an appendix) to this report: 1) Introduction; 2) Ground truth and LiDAR data collection and processing; 3) Extraction of forest metrics from LiDAR point cloud data; 4) Presentation of results; 5) Scan configuration options; 6) Concluding remarks. Prior to presenting the data analysis, a brief overview of the ILRIS 3D imager shall be provided.

ILRIS is a tripod-mounted eye safe LiDAR (Light Detection And Ranging) imaging system manufactured by Optech Incorporated. The instrument emits 2000 laser shots per second across a horizontal and vertical field of view of 40 degrees. Either the first or last pulse reflected back to the unit from each shot emitted can be directly digitized and stored. Ranges of up to and over 1 km can be recorded. The scan settings can be user configured either for speed of data collection or for high data density. For example, a typical scene of 1.2 – 1.8 million points will be acquired in 10 – 15 minutes. At distances of 50 m away from the ILRIS sensor, the laser pulse has an approximate size of 15 mm diameter, with spot spacings as low as 10 mm. This effectively gives ILRIS the capability to "paint" the entire 40 x 40 degree field of view at distances up to 100 m. This remote capability of a rapid and dense measurement sampling rate could make ILRIS a useful tool for assessing forest biometric properties. It is the aim of this report to test this potential capability.

2 Data Collection

2.1 Study Area

Forest environments are widely variable in terms of species composition, structure, height and biomass characteristics. It would be impossible to adequately represent the entire cross-section of forest environment types in a study such as this but an effort was made to investigate two distinctly different site types common in the southern Ontario geographical context. The two sites investigated are:

1. a mature red pine plantation with little to no understory;
2. a multi-tiered deciduous stand dominated by sugar maple, hickory, and basswood trees of varying ages.

Both of these sites are located in the North Tract of York Regional Forest (often referred to as "Vivian Forest"), about 50 km north of Toronto (Figure 1). LiDAR forest research has been ongoing within this area since the summer of 2000, and various plots had previously been identified in related studies. Within the broader context of the Vivian Forest LiDAR research project, the plots chosen for study here are known as plot 4 (red pine plantation) and plot 6 (deciduous stand). Each plot has approximate dimensions of 45 m x 45 m. Due to site constraints, the size and orientations of the plots are not quite regular or uniform. The ground conditions at each site are illustrated in Figure 2.

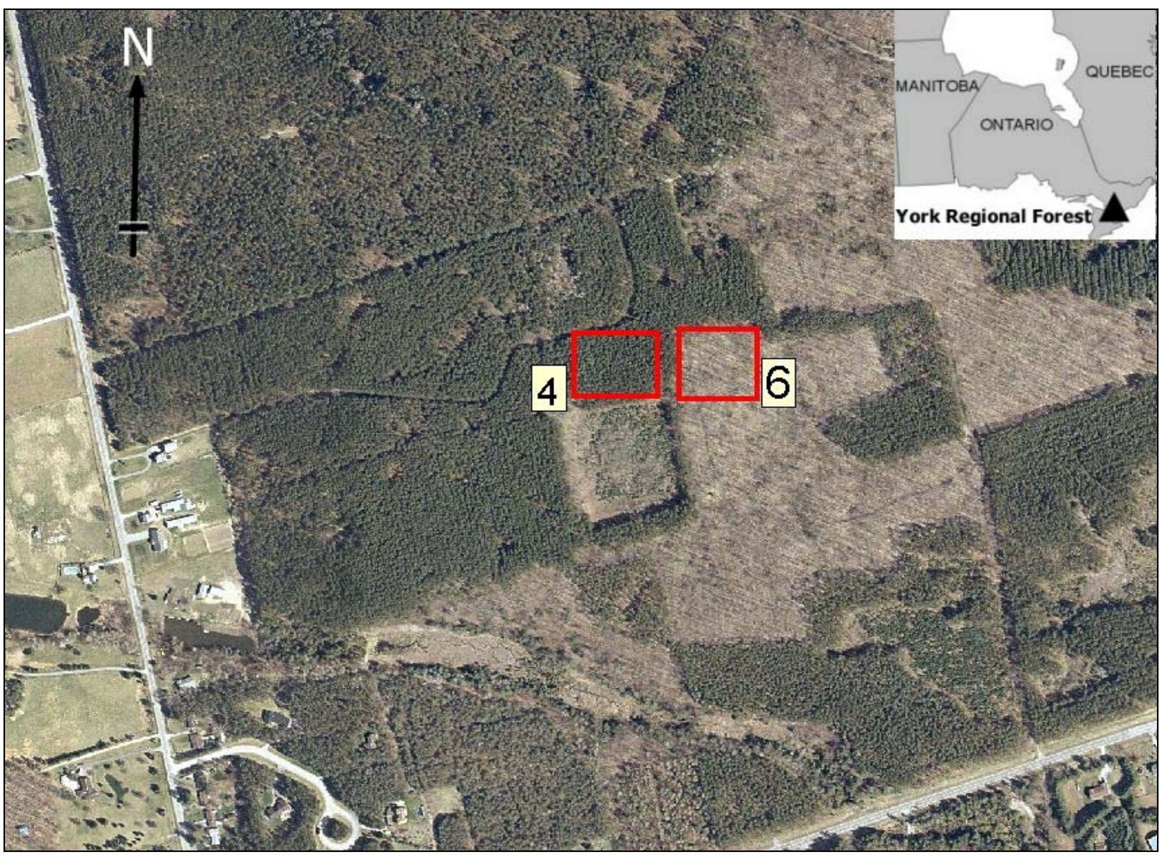


Figure 1 Vivian Forest ILRIS sample plots, 50 km north of Toronto. Plot 4 = mature red pine conifer plantation; plot 6 = multi-tiered mixed deciduous (predominantly sugar maple). Air photo acquired in Fall 1999.

Figure 2 Ground conditions for the red pine plot 4 (left) and the deciduous plot 6 (above). Note the lack of understory and stand homogeneity in the pine plot, and the presence of leafy biomass at all levels in the deciduous plot. Both pictures were taken near the time of the ILRIS survey.

The majority of the data presented in this study were collected from the 4th to the 17th of July. Both plots were identified and marked out with string on the 4th of July in readiness for the ILRIS survey the next day. Following this, intensive field data collection was carried out by two people for the purpose of validating both ILRIS and ALTM derived forest biometric data. There were 179 trees surveyed in plot 4 and 143 in plot 6, and each tree was identified with a unique ID tree tag. Not all of the field data collected were needed for this study and in the case of both the ILRIS and ground truth data collection the tasks were carried out by persons somewhat unfamiliar with forest data collection. Therefore, the times taken for data collection cannot be considered representative of normal field operations.

2.2 Forest Mensuration Ground Truth

2.2.1 Position of tree stems

The first attempt at locating all the trees utlised a Trimble Pro XRS mapping grade DGPS with a nominal accuracy of better than 0.5 m rented from Cansel in Toronto. There were no known survey control markers in the vicinity of the plots and so GPS initialization was conducted over unknown control markers on the highway just over 1 km to the west of the plots. Following initialization several attempts were made to walk into the site along major pathways from the road without losing lock. Unfortunately, poor satellite geometry and canopy shadowing led to a loss of lock on every occasion. It was thus decided to initialize from within the plots and move carefully from tree to tree. This did work for some trees but was very time consuming due to continually losing lock.

Figure 3 Initialising the Trimble Pro XRS at the roadside.

Following GPS surveys, the raw data were downloaded to PC for differential GPS post-processing using base station data collected at Cansel in Toronto. Unfortunately, after several field surveys and attempts to optimise the processed solutions, the locational data were found to be up to several metres out in some cases, and generally not suitable for the purpose of locating trees within heavily canopy covered areas. The main problems were thought to be poor satellite geometry, signal multipath and relatively short lock times.

The next method adopted for locating the trees within the pine plantation plot was to use a prototype inertial survey instrument known as the "POS (position orientation system) Backpack", manufactured by *Applanix*. This system uses the same kind of inertial measurement unit (IMU) that is used (in combination with DGPS) in airborne survey aircraft and missile guidance systems to enable highly accurate four-dimensional positioning. The IMU precisely monitors three-dimensional accelerations through time to keep a constant fix on current position. Therefore, if the initial control point of the IMU prior to a survey is known, then points subsequently visited can be stored and related to the original control point.

Figure 4 POS Backpack system

Approximately 75% of the trees in plot 4 were measured in this manner and referenced to a temporary GPS control point (used for IMU initialization) on the highway just over 1 km away. After completing the POS Backpack survey, the instrument was taken back to the initialization point and it was found that after almost three hours of beneath canopy survey time, the instrument had drifted by less than 2 m. The data were then post processed by Applanix and after correcting for the drift, there is high confidence that the relative tree stem locations surveyed should be accurate to within 1 m (see Figure 5 for an illustration of POS tree location data). Unfortunately, it was not possible to survey in all the trees due to time constraints. The remaining trees were located using tape and bearing techniques. For plot 4 this should not introduce much error, as there was always a tree of known position close by that could be used for reference. However, for plot 6 all trees were referenced to a central "control" tree stump and it is estimated that locational errors could be greater than 2 m in X and Y at the edges of the plot.

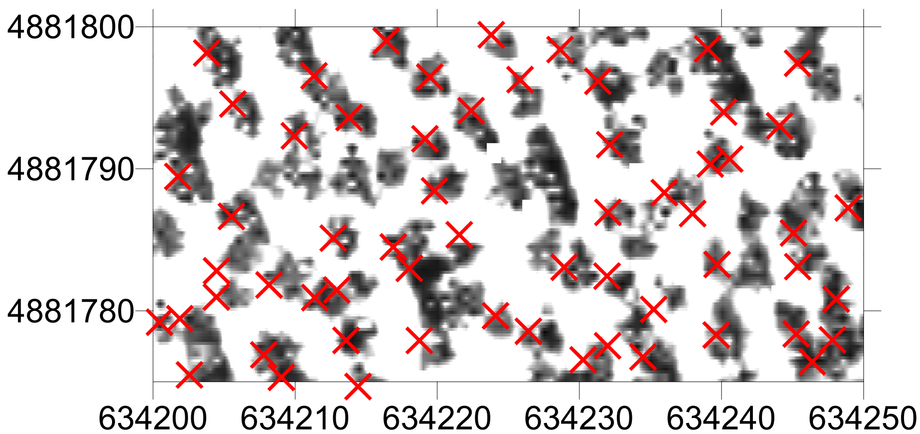


Figure 5 An illustration of the POS Backpack tree stem locations (red crosses) overlain onto a forest canopy model derived from airborne laser terrain mapper (ALTM) data collected within the Vivian Forest. Not all trees were surveyed but for those that were note the close correspondence between POS tree stems and ALTM tree crowns.

2.2.2 Tree height

Tree height and height to live crown was measured for all trees using a sonic clinometer. Measurements were taken to the top of the live crown and to the bottom of live crown (live crown visually defined as > ~ 10% leaf cover on branches). It is estimated that in some cases these manual height estimates could easily have an associated error of 1 m – 2 m due to the difficulty of observing the true tops of trees that are visually obstructed. It should also be noted that although the bottom of live crown was measured in the field, there was insufficient time to investigate this parameter with the ILRIS data. However, tree tops are more difficult to observe than the bottom of live crown due to canopy shading effects, and so it was assumed that if ILRIS data could successfully estimate tree height, then assessing the height of live crown should be a relatively straight forward task.

Plot level tree height averages were calculated along with Lorey's tree height (more stable than average height because it is less affected by mortality and harvesting of smaller trees) to facilitate plot level comparisons with ILRIS derived height data. The equation for Lorey's tree height h_l is:

$$h_l = \frac{\sum g \times h}{\sum g} \qquad (1)$$

where g = basal area;
h = tree height.

2.2.3 Stem diameter at breast height (DBH)

Tree stem diameter was measured for all trees at approximately 1.5 m off the ground using a 7.5 m *Canadian Forestry Equipment* (CFE) DBH tape measure. Although it is common practice to only measure the DBH of tree stems with a diameter greater than around 9 cm, for this study all trees with a height above 2 m have been measured for DBH. This allows a much greater range of measurements to be recorded and therefore facilitates a more thorough test of ILRIS capabilities.

2.2.4 Crown diameter

Crown diameters for all trees were measured using a 7.5 m standard tape measure. Tree crown radii or diameters were measured at both north to south and east to west directions. The tape was held at the centre of the stem while one person moved away from the stem and looked up into the canopy to subjectively estimate the horizontal extent of the live crown (see Figure 6). The error associated with this measurement is largely a function of personal judgement and the amount of visual obstruction between the observer and the crown. Errors will be greatest for the taller trees in the deciduous plot 6.

Figure 6 Subjectively estimating tree crown radius for the four points of the compass.

2.2.5 Forest mensuration statistics

From the data collected above, summary statistics of the major forest biometric parameters were calculated to facilitate comparisons with similar parameters estimated from the ILRIS point cloud data. The statistics generated for each plot were:

- Area (Ha)
- Mean DBH (cm)
- Total basal area (m^2/Ha)
- Mean tree height (m)
- Max tree height (m)
- Lorey's tree height (m)
- Stem density (#/Ha)
- Gross total tree volume (m^3)
- Merchantable volume (m^3)

Gross total and merchantable volumes for both plots were estimated using allometric equations used by the local forest manager (Chris Gynan, Silv-Econ Ltd. Pers. Comm.). The allometric equations were originally developed for the Petawawa research forest northwest of Ottawa, and they utilise tree DBH and height for volumetric estimations (Bonnor and Magnussen, 1986). Volume estimates were made using both the ground truth and ILRIS derived height and DBH measurements. The specific equations used were:

$$V_t = \frac{C_1 D^3}{\left(a_1 + \frac{b_1}{H}\right)} \qquad (2)$$

where V_t = gross tota1 volume (m^3);
D = stem diameter at breast height (cm);
H = total tree height (m);
a_1, b_1, c_1, = regression coefficients (from appendix 4 in Bonnor and Magnussen, 1986).

$$V_m = V_t\left(a_2 + b_2 X + c_2 X^3\right) \quad (3)$$

where V_m = gross merchantable volume (m^3);
a_2, b_2, c_2 = regression coefficients (see Bonnor and Magnussen, 1986);
and:

$$X = \left(\frac{d}{D}\right)^2 \left(1 + \frac{h}{H}\right) \quad (4)$$

where d = top diameter inside bark = 7 cm;
h = stump height = 30 cm.

2.3 ILRIS Data Collection

Plots 4 and 6 were surveyed with an Optech Incorporated ILRIS 3D laser imager in approximately six hours on the 5th of July 2002 (see Figure 7). The crew conducting the survey had no prior experience with LiDAR forest data collection of this nature, and the optimal scan configuration for this task was unknown prior to commencing the survey. It was decided, however, that for each plot, all scans would originate outside of the plot boundaries and converge on a control point somewhere near the centre. Unfortunately, some of the scans were collected from within the plot boundary of the conifer plot 4 and so the size of area ultimately investigated was reduced to a square plot of 35 m x 35 m. For consistency, the deciduous plot 6 was also reduced to the same size. See Figures 8 and 9 for the ILRIS base station locations and their proximity to the final plot areas sampled.

Figure 7 The ILRIS 3D laser imager in action in the Vivian Forest, north of Toronto.

Six scans of data were collected for each of the conifer and deciduous plots. However, one of the scans at each plot was essentially redundant due to nearby obstacle shading and the need to move the ILRIS very slightly to improve the field of view (see Figures 8 and 9). Other scans were collected but have not been included in the raw point cloud data presented in this report. For details of the ILRIS instrument settings see Appendix 1 for copies of the operators logs for all scans collected. In addition to the 12 scans into the two plots, two more were collected along an adjoining pathway between the two plots to facilitate coregistration of the two data sets. In order to ensure that individual scans could be registered (or aligned) to each other, small control marker targets that were visible from multiple directions were erected in each of the plots. Four of these control marker locations were subsequently surveyed in using DGPS so that the ILRIS point cloud data could be georegistered.

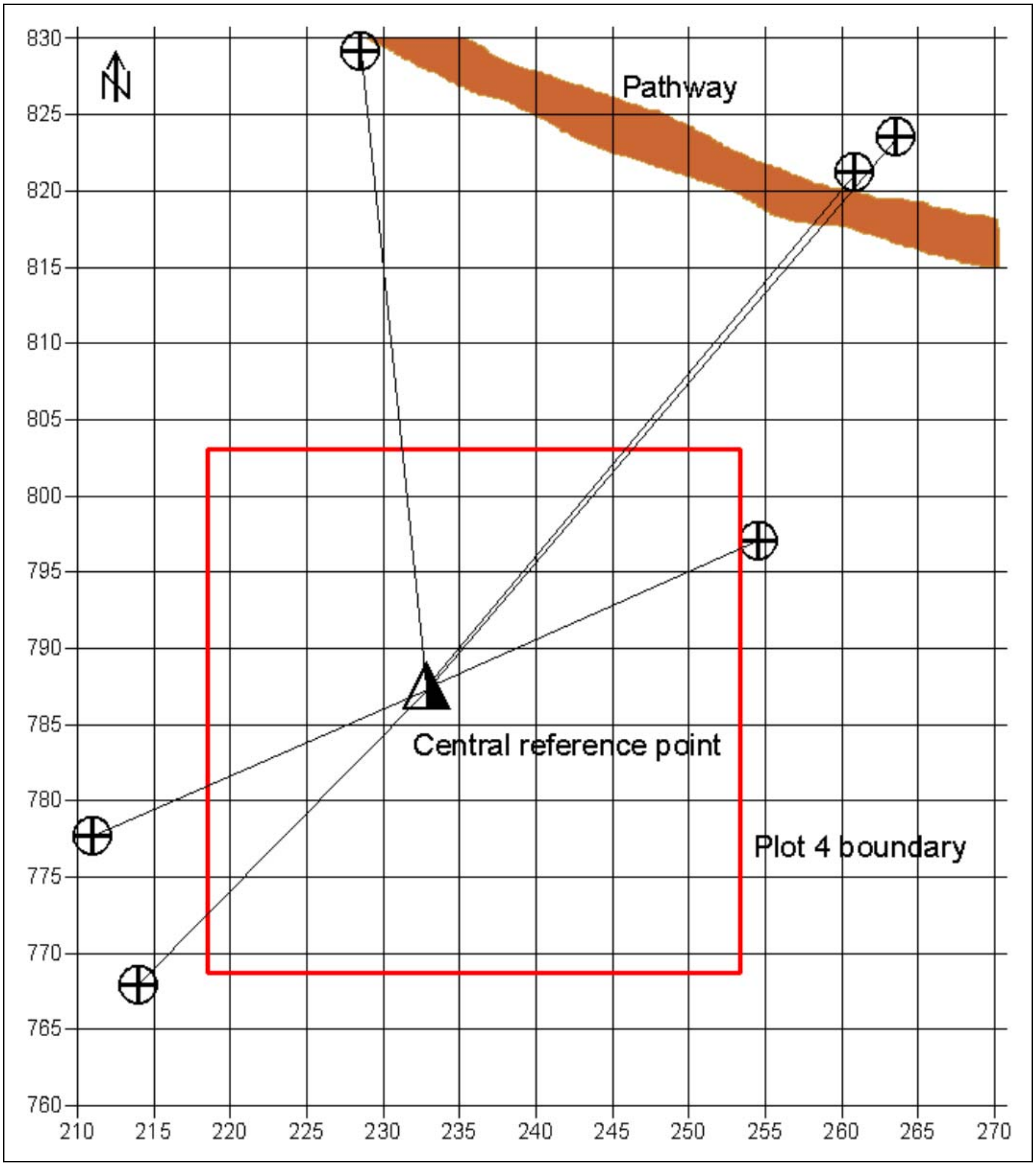


Figure 8 ILRIS base station locations around the conifer plot 4. (Easting and northing co-ordinates are truncated.)

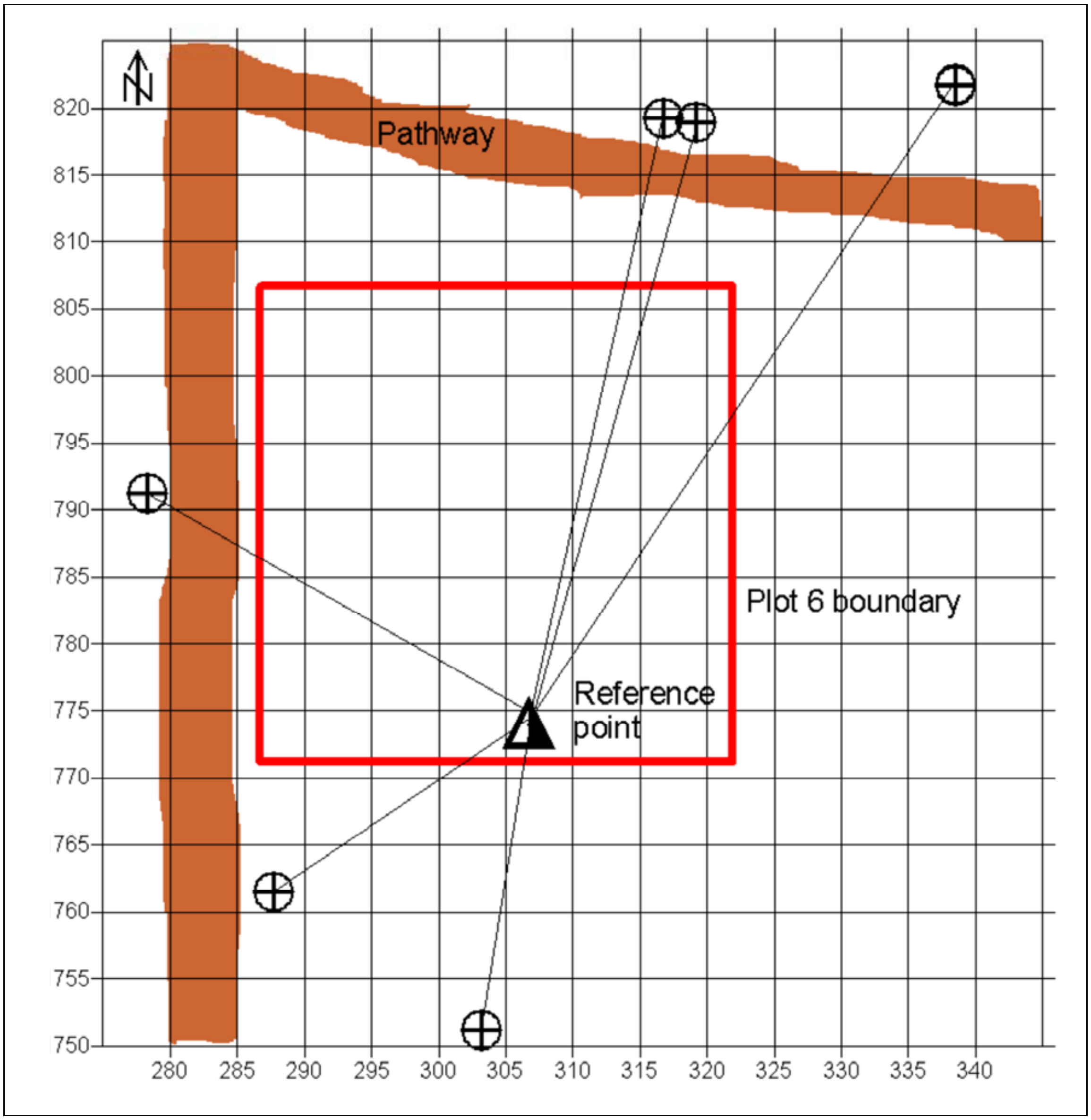


Figure 9 ILRIS base station locations around the deciduous plot 6. (Easting and northing co-ordinates are truncated.)

After collecting the raw ILRIS scan data, the point clouds for each scan were aligned and georegistered. This procedure was carried out by Optech prior to delivery of the data. Due to high complexity within the 3D point could data combined with a lack of easily distinguishable features within both forest plots, aligning the data was found to be problematic and very manually intensive. After the first attempt at aligning the data in the *Innovmetric* "Polyworks" software suite ("IMALIGN" module), it was found that many tree stems and canopies did not match up perfectly (see Figure 10). After further manual manipulation of the data, an acceptable alignment of most of the scans was achieved. [*This difficulty highlights the need for easily identifiable and plentiful ground control points within the scan scene if ILRIS is to be adopted in similar future survey applications.*] Following alignment of all the scans, the merged raw point cloud data (truncated UTM easting, northing, elevation co-ordinates plus intensity) were ready to be analysed for forest metric information content.

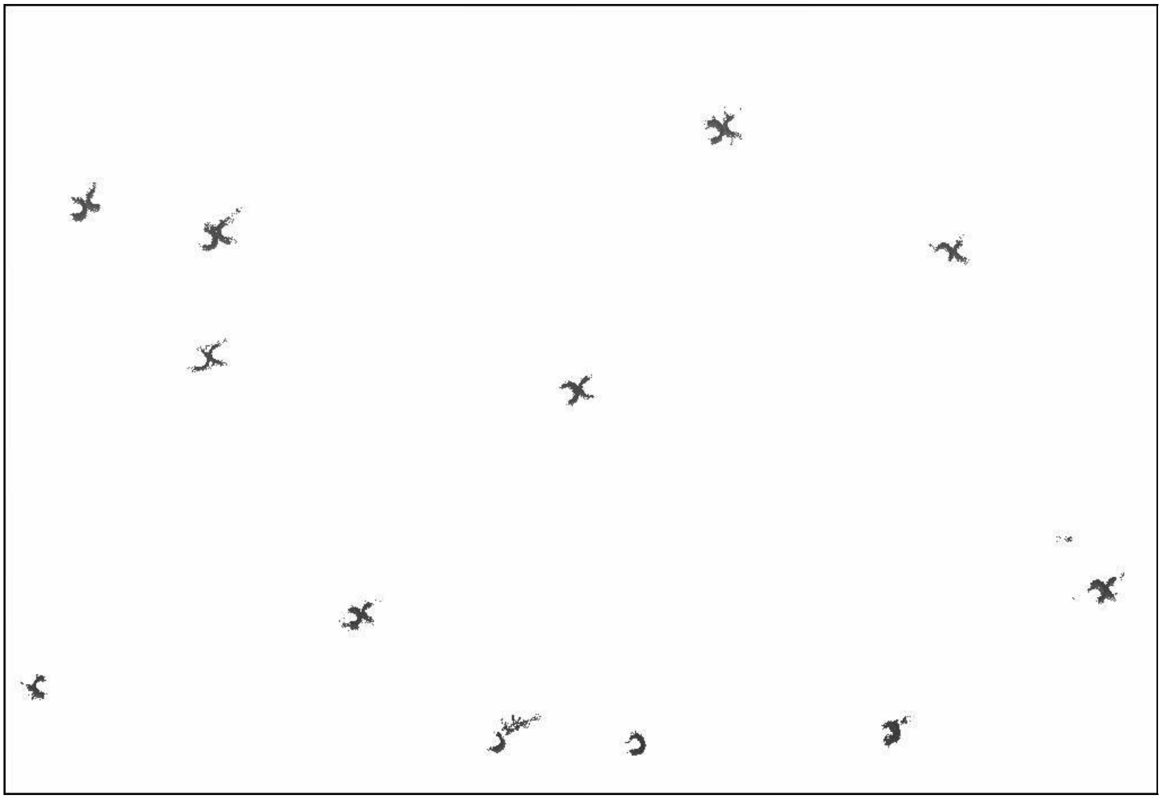


Figure 10 Vertical slice through merged ILRIS point cloud data near centre of conifer plot 4 between heights 252 m to 253 m a.s.l. after preliminary scan alignment. Note tree stem arcs from opposing scan sides have been merged on the "face" side rather than the "inside" of the stem. This problem was almost completely removed following a secondary alignment of the data.

3 ILRIS Data Analysis

3.1 ILRIS Scan Coverage

The proportional scan coverage within each 35 m x 35 m plot was assessed so that ILRIS based estimates of tree count and stem density could be compared with those from manual measurements. A higher confidence in data generated in areas of multiple scan overlap would be expected and so it was considered appropriate to quantify scan coverage both for the amount of the plot represented by a single scan, and the amount of the plot covered by three overlapping scans. These quantities were estimated by overlaying the scan boundaries onto the plot boundary, measuring the within plot areas covered by all scans and overlapping scans, and then comparing these sub-areas with the overall plot area.

3.2 Tree Locations and Numbers

Mapping tree locations tends to be a difficult task. GPS instrumentation is unreliable in canopy-covered environments and traditional theodolite surveys require many control point locations and line of site between all fore sights and back sights. Tape and bearing techniques can be used but these are time consuming and imprecise. Therefore, although the main objective of this report is not to investigate the ability of ILRIS for tree locationing, it would constitute a significant bonus if it could be. Of more importance in the forest mensuration context is the ability to count the number of trees within a plot. However, if it can be shown that tree location can be determined, then the task of counting trees should be trivial by comparison.

In order to manipulate the data into a format that could be used for identifying tree location and number, it was assumed that each tree would have a distinct tree stem that would be a distance several factors greater than the stem diameter away from adjacent stems. If this assumption were valid, it would be possible to isolate individual tree stems from the point cloud data, and then count and locate each tree within a plot. In order to isolate tree stems, it was necessary to remove the point cloud data associated with the ground, tree canopies and low understory. This was attempted by vertically slicing the entire plot point cloud in each plot to leave a horizontal layer of data that corresponded predominantly with tree stems only. For the conifer plot 4 this was relatively straightforward and the horizontal layer chosen corresponded with heights that were approximately 1 m to 4 m above the average ground height. For the deciduous plot 6, a greater vertical range was chosen corresponding to approximately 2 m to 7 m above average ground height due to the multiple canopy levels within the plot.

Ultimately, it would be beneficial if tree locations and tree counts could be carried out automatically. Assuming the above-described vertical slicing methodology could adequately separate out tree stems from canopy and ground and represent each individual tree, then there would be the possibility of running a spatial filter over the remaining point cloud data to identify regions of the plot that have a high likelihood of containing a tree. Unfortunately, it was out of the scope of this study to research this aspect of automation but a manual assessment was carried out, nonetheless.

After slicing the ILRIS data to leave behind a tree stem layer, the POS derived tree location map was overlaid onto the remaining point cloud layer to assess which trees were visible, which were not and whether there were any other features that could be mistaken for trees. For those point cloud tree stems that were easily identifiable as corresponding to specific POS surveyed trees, the tree stem centre co-ordinate was noted (co-ordinates were easily generated within the Polyworks software environment by fitting either a vector or cylinder "primitive" to the point cloud – discussed in sections 3.4 and 3.5). These ILRIS derived tree counts and locations could then be directly compared with the field ground truth data (see Figures 11 and 12).

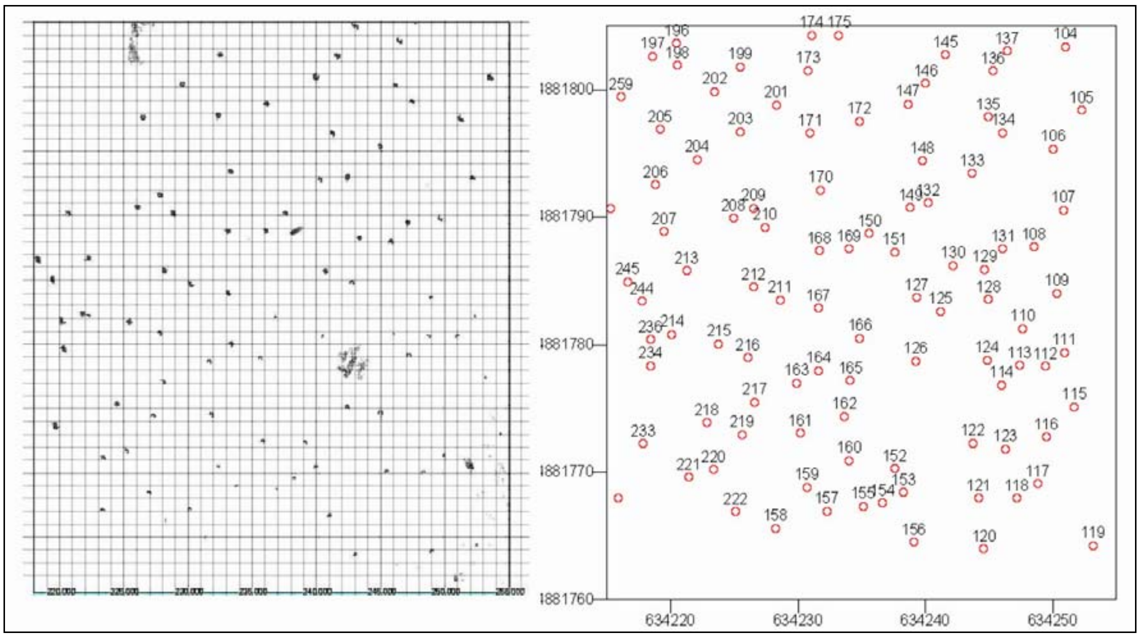


Figure 11 ILRIS point cloud tree stem map (left) and POS tree stem map (right) for conifer plot 4.

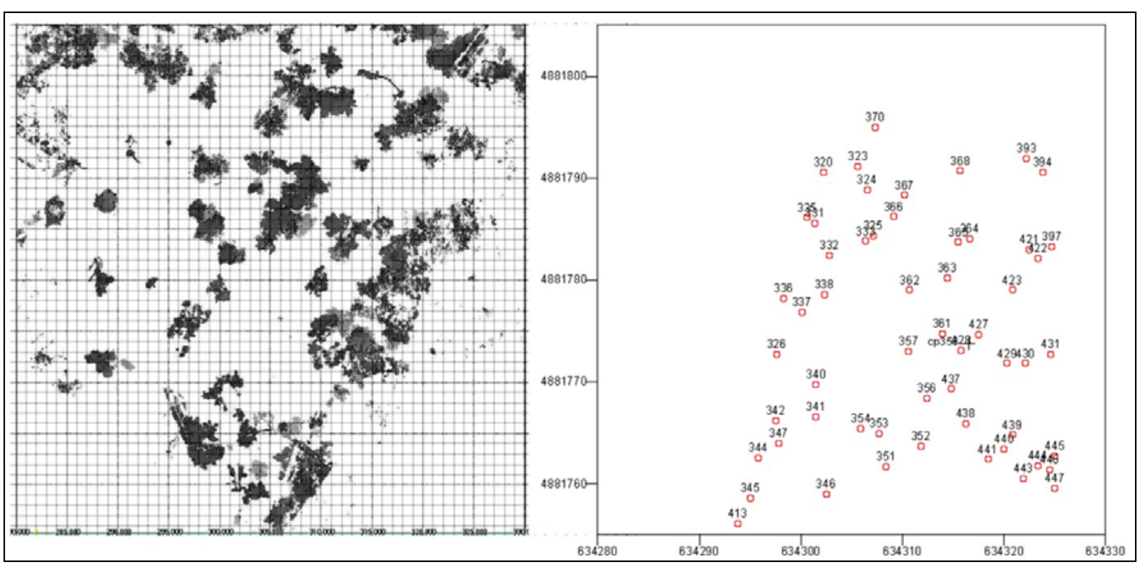


Figure 12 ILRIS point cloud tree stem map (left) and POS tree stem map (right) for deciduous plot 6.

3.3 Extracting Trees from the ILRIS Point Cloud

Before the assessment of ILRIS derived tree metrics was carried out, individual trees were extracted from the plot point cloud and written to separate files that were numbered according to the tree tag identifiers placed on each tree when in the field. This was somewhat time consuming but made subsequent analyses easier and quicker, and ensured that ILRIS derived data were directly comparable with the ground truth. This task was performed in the *Innovmetric* Polyworks software environment, using the "IMINSPECT" module. Tree data extraction was objective and semi automated in that tree locations were already known (from the POS/ILRIS tree location comparison) and so the point cloud for each tree could be selected based on its centre co-ordinate and an assumed radius. The assumed radius was set slightly larger than the maximum field measured crown radius for each plot. In virtually all cases this generated point cloud files for each tree that extended beyond the true boundary of the tree and often included bits of canopy and limbs from neighbouring trees. Therefore, after writing out all the tree point cloud files, they were all manually "cleaned" up to remove superfluous data. See Figures 13, 14 and 15 for examples of the "cleaned up" tree level point cloud data.

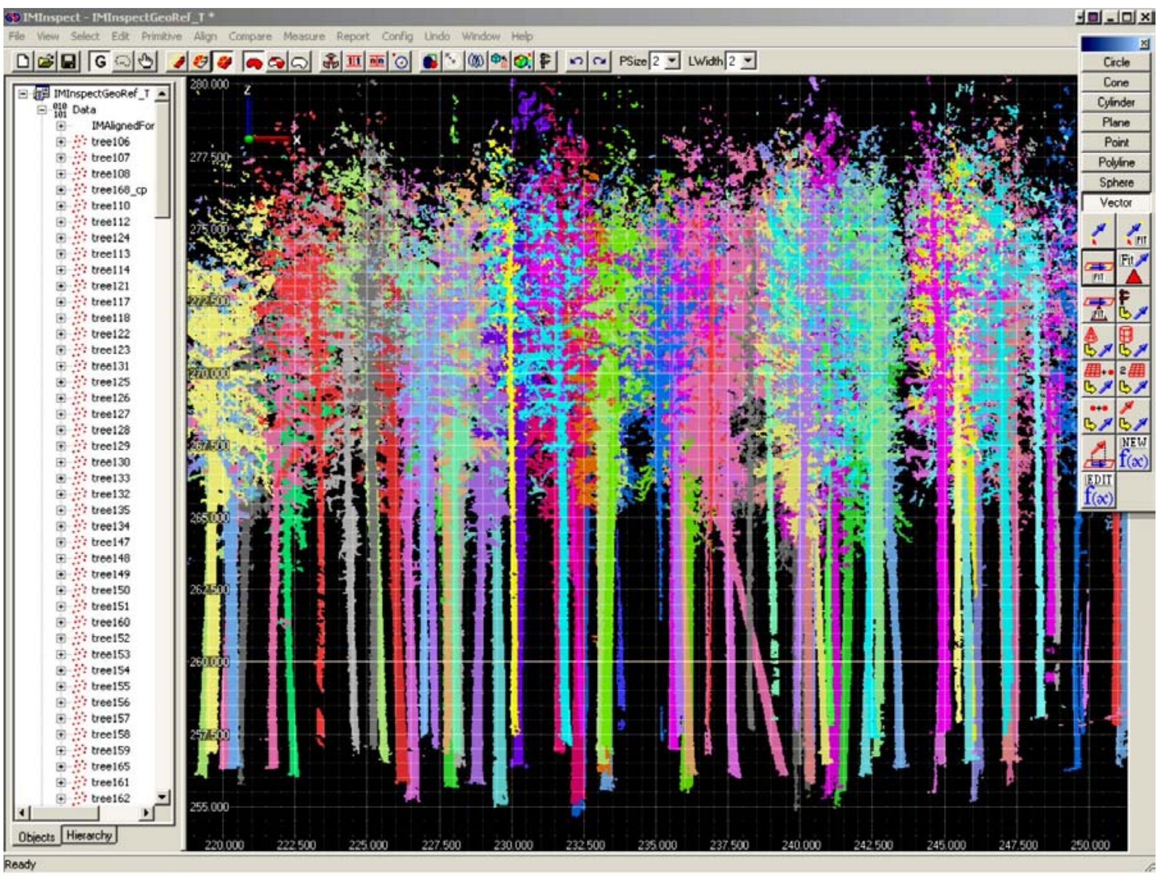


Figure 13 Oblique view of individual ILRIS tree point cloud files within the Polyworks' IMINSPECT module. Red pine conifer plot 4.

Figure 14 Side view of individual ILRIS tree point cloud files. Mixed sugar maple deciduous plot 6.

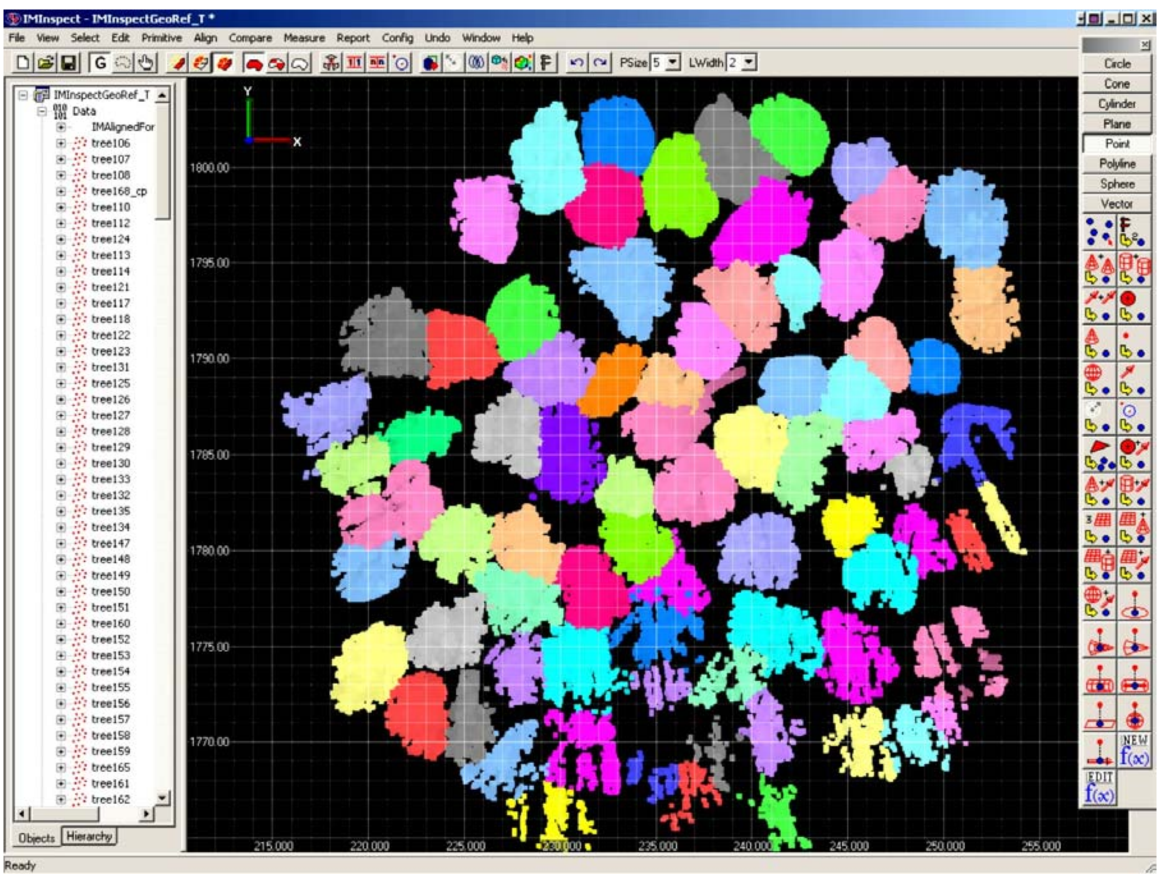


Figure 15 Plan view of individual tree canopies in Polyworks IMINSPECT module. Red pine plot 4.

3.4 Tree Height

After individual trees had been written to separate files, it was possible to bring each separate file into IMINSPECT and manually fit a vector primitive to the data corresponding with the visible height of the tree (see Figure 16). This procedure was made objective by specifying that the vector must join the lowest and highest laser shots within the individual tree point cloud file. After this procedure had been completed for all tree files, the vector attribute data were directly outputted to a spreadsheet for subsequent analysis.

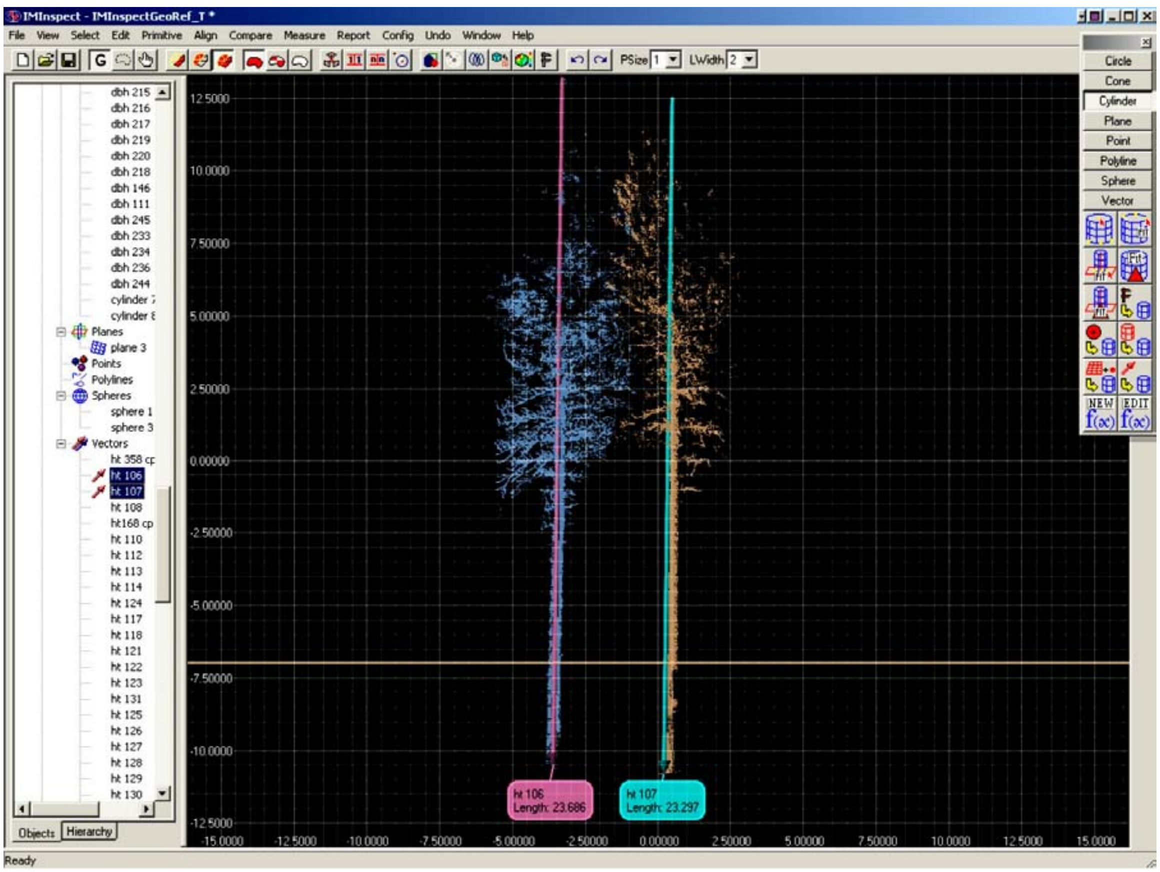


Figure 16 Tree height estimation using vector primitives from highest to lowest points in the tree point cloud.

3.5 Stem Diameter at Breast Height

Tree stem diameter for the ILRIS tree files was estimated by selecting all tree stem data that lay between 1.25 m and 1.75 m vertically above the lowest elevation point in the file, and then fitting a cylinder “primitive” to the data (see Figure 17). There were various options that could be changed in this procedure and for the purpose of this analysis a simple least squares best fit to the point cloud data was chosen. After this procedure had been completed for all tree files, the cylinder attribute data were directly outputted to a spreadsheet for subsequent analysis. Following the end of the software license evaluation period, a better technique was discovered that forced the cylinder to fit the point cloud data while also restricting the cylinder axis to a vertical line. Had this procedure been adopted, there is high confidence that the results would have been improved. As is, the data presented in this report have been derived in the simplest manner possible.

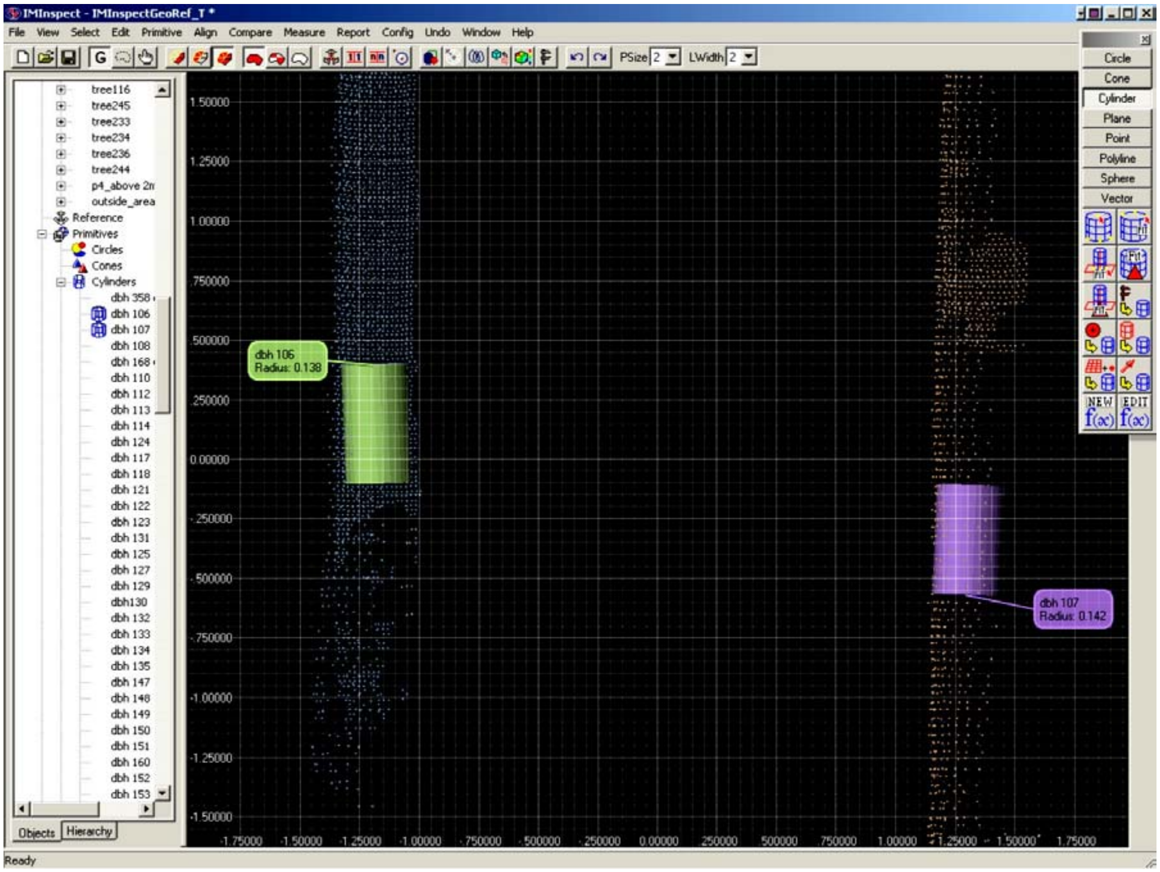


Figure 17 Tree stem DBH estimation using simple cylindrical primitives fitted to the tree stem between 1.25 m and 1.75 m above the lowest point in the file.

3.6 Tree Crown Diameter

No objective methods of estimating tree crown dimension could be found or tested, so for the analysis presented here little attention was paid to this important forest metric. However, for the sake of illustration, subjective measurements of crown diameter were made for three trees using "digital calipers" in IMINSPECT that can be manually dragged across the feature of interest to measure its dimensions (see Figure 18). With more time on the software license demonstration period, it would have been possible to do a more complete evaluation of this technique and/or test other possible means of extracting tree crown information.

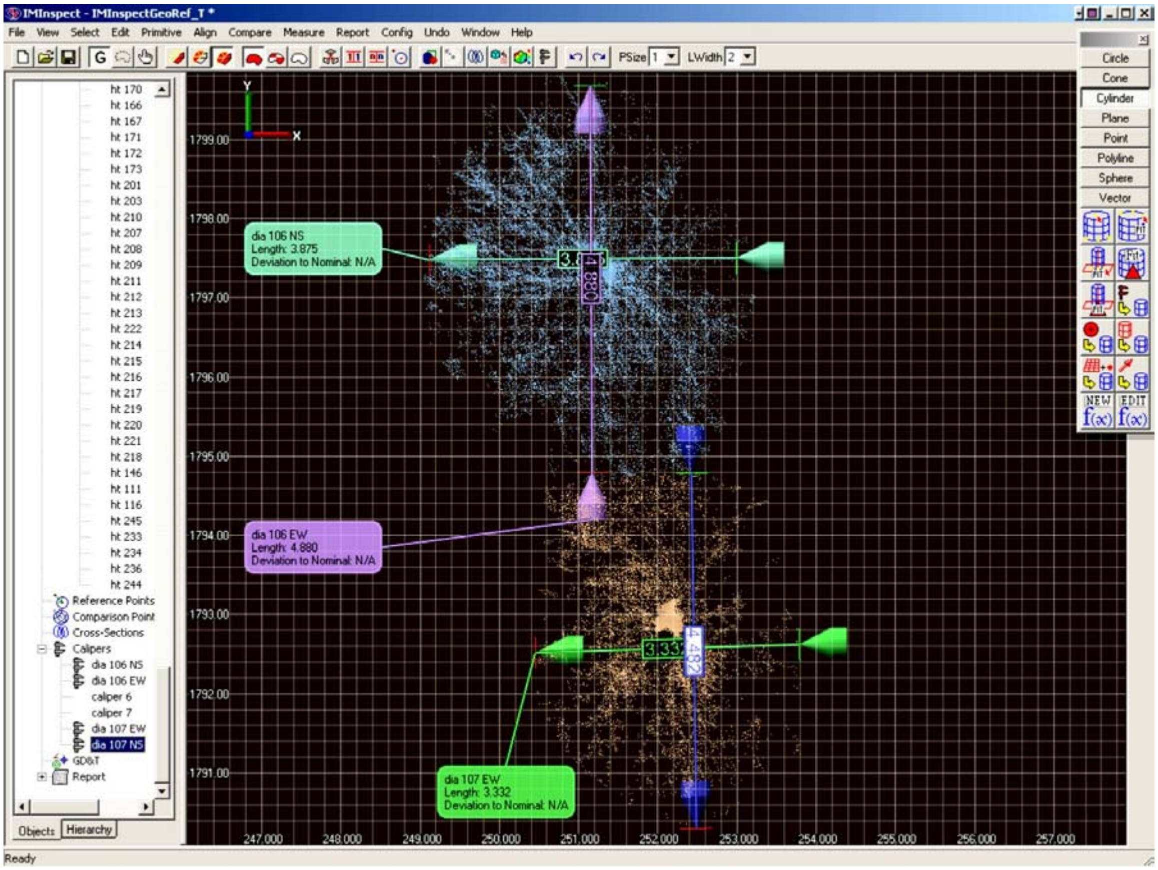


Figure 18 Fitting "virtual calipers" to individual tree crowns to estimate crown diameters in IMINSPECT.

<u>3.7 Planimetric Canopy Gap Fraction</u>

During the field ground truth data collection, canopy gap fraction was measured using hemispherical photography from the ground up into the canopy (data not presented in this report). This technique essentially quantifies the level of open sky exposure at a point on the ground. Although it is possible that the same estimation could be made more objectively using the 3D ILRIS point cloud data, this was not tested in this proof of concept as it would require specialized software or the development of new code to extract this information. However, a similar and more readily quantifiable parameter is the "planimetric canopy gap fraction" (PCGF).

For a single tier canopy with no overlapping tree crowns, the PCGF could be considered very similar to the inverse of the ellipsoidal crown closure ratio. For multi-tiered canopies, assessing the total canopy openness can be challenging and is not easily quantified from simple measurements of crown diameters. Above ground remote sensing techniques for assessing this parameter are fraught with difficulty due to sampling resolution and the difficulty of separating ground, understory and canopy. There are ground based field techniques that can measure canopy openness (other than hemispherical photography) but they tend to be "sampling" techniques and thus do not actually measure total canopy openness. ILRIS data offers the potential of sampling the entire spatial canopy domain and not just small possibly unrepresentative chunks of space. For this reason, canopy openness estimates from ILRIS offer the potential to be the standard to which other techniques may be compared.

This is a topic that could be the subject of several reports and papers itself, and it is not within the scope of this proof of concept to do a thorough analysis here. However, a simple estimate of PCGF was made for both plots by simply removing the bottom 2 m of data at ground level and then exporting the plan view of the remaining point cloud to a bitmap image. This image was then converted to a binary bit plane so that the number ratio of active cells could be compared with the number of inactive cells within the plot and converted to a fraction.

A problem with this simple technique is that it assumes the spatial canopy domain has been fully sampled by the ILRIS scans. Therefore, it would be logical to assume that the most accurate estimates of PCGF would occur in areas of overlapping scans to avoid errors due to shadowing. The plots were thus divided into areas according to scan overlap (plot area covered by a single scan and plot area covered by three or more scans) and PCGF calculated for both areas. See Figure 19 for an illustration of the bit plane areas corresponding to single and three scans, and the corresponding PCGF.

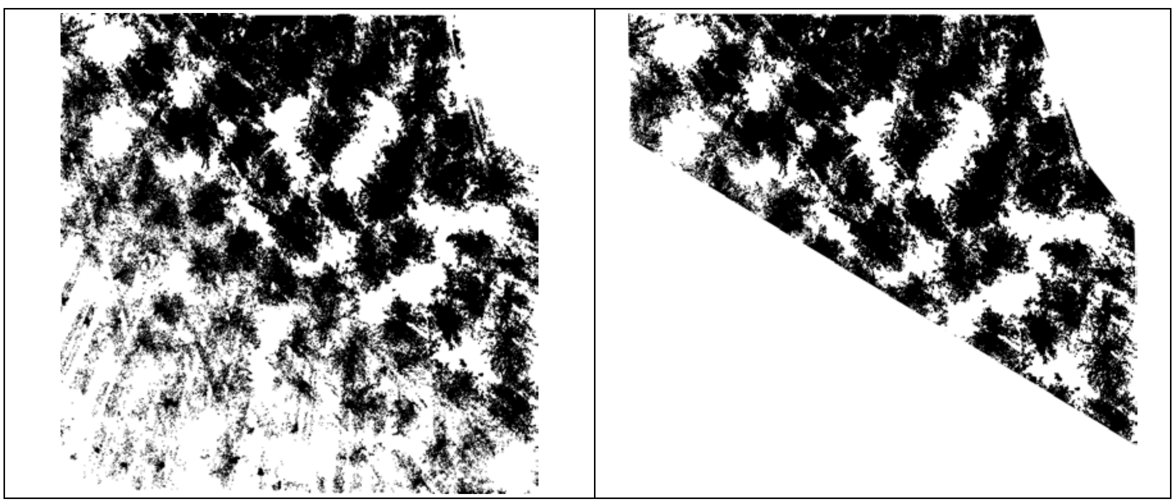


Figure 19 PCGF image with ground level data removed for conifer plot 4. Entire plot area (left) and three scan overlap area (right).

3.8 Vertical Biomass Profile

Given that 3D laser point cloud data effectively sample the entire spatial canopy domain within a plot, the structure and volume of biomass within the plot is directly digitised. However, although the information is contained within the data, methods need to be developed to extract this important information. A simple method illustrated here, is to vertically slice the point cloud and plot a vertical profile of laser point density within each elevation band. This is a rather unsophisticated approach to assessing biomass structure and volume but is included here for the purpose of illustration only. Further in-depth analysis of this problem is currently ongoing.

3.9 Test of Techniques using Single Scan Data from Southern Ireland

During the course of this analysis, a dialogue was initiated between the author and *Mapex Europe* to investigate the possibility of "operationalising" the use of ILRIS for European plantation forest inventory applications. To this end, further ILRIS scan data were collected by Optech Incorporated within a sitka spruce plantation in Southern Ireland and subsequently ftp'd to the author for analysis. The data arrived the evening prior to the end of the Polyworks software evaluation period and so only a quick assessment could be performed. The forest mensuration data derived for this sitka spruce plantation were derived in the same manner as described above but of note is that all parameters were estimated from a single unaligned and ungeoregistered scan. Unfortunately, no ground truth data were available to test the accuracy of the derived data but the ILRIS data are included here as an illustration that mensuration statistics can be generated rapidly; i.e. the single scan took about 15 minutes to collect, and the subsequent manual processing took less than three hours.

4 Results and Discussion

4.1 Scan Coverage and PCGF statistics

Area	35 m x 35 m (0.123 Ha)
Total coverage with at least 1 scan	95% (0.117 Ha)
Coverage with 3 or more scans	51% (0.062 Ha)
PCGF (all)	45%
PCGF (3 scan overlap)	38%

Table 1 Plot 4 conifer ILRIS scan statistics

Area	35 m x 35 m (0.123 Ha)
Total coverage with at least 1 scan	> 97% (> 0.119 Ha)
Coverage with 3 or more scans	69% (0.085 Ha)
PCGF (all)	45%
PCGF (3 scan overlap)	30%

Table 2 Plot 6 deciduous ILRIS scan statistics

Both plots have the same area but the amount of complete scan coverage varies, with plot 6 displaying almost complete aerial coverage at over 97% (69% with three scans), and plot 4 around 95% (51% with three scans). The greater single and multiple scan coverage for plot 6 can be attributed to a more even distribution of ILRIS base locations around the plot. Subsequent statistics are corrected for the total area of single scan coverage; e.g. ILRIS derived plot stem density (#/Ha) is calculated from the number of trees observed within the total plot area that contains any scan coverage.

For both plots the PCGF was around 45% for the entire plot area but when this value was computed using only areas covered by at least three scans, the PCGF dropped. [*This illustrates the influence of scan shadow effects and the need to minimise them through optimal scan configurations (discussed in section 5)*]. The drop was the least for conifer plot 4 at only 7%. Of note is that the new PCGF of 38% was relatively close to the inverse of the manually measured ellipsoidal crown closure ratio (ECCR) of 68%. As stated earlier, for a single tiered canopy, the PCGF and ECCR can be considered almost the inverse of one another. Although the red pine canopy in plot 4 was uniform and single tiered, the PCGF value of 68% was higher than would be predicted from the measured ECCR (i.e. 62%) because ECCR does not account for “holes” within individual crown radii or irregular shaped crowns.

For the deciduous plot 6, the three scan PCGF dropped to 30% from the single scan value of 45%. (No comparison could be made between PCGF and ECCR due to canopy layering.) This large change in value was thought to be the result of increased canopy layering and generally higher levels of biomass in the deciduous stand than in the conifer plantation. This suggests that optimizing scan configuration to minimise shadow effects is far more critical in multi tiered "natural" forest stands than in managed and highly uniform conifer plantations.

[*A supplemental note here is to suggest that ILRIS derived PCGF, although perhaps not a standard measure, may prove itself useful for a variety of applications. For example, it could be used as a parameter in simple radiative transfer models, and it could be used to define the precipitation interception ratio within a forest stand.*]

4.2 Tree Locations and Stem Density

The number of manually measured trees above 2 m in height was 81 in the conifer plot 4 and 57 in the deciduous plot 6. The number of ILRIS defined trees for each plot and the associated horizontal positional errors are presented in Tables 3 and 4. The proportion of the total number of trees within each plot that were extracted from the ILRIS data approximately corresponded to the total aerial scan coverage proportion; i.e. for the conifer plot, the 77 trees that ILRIS could see equaled 95% of the 81 trees within the plot, and this proportion also equaled the plot area that was covered by at least a single scan. Therefore, the stem density estimate of 661 stems/Ha for plot 4 was identical using both techniques. For the deciduous plot, all 57 trees were identified within the ILRIS data despite a scan coverage of > 97%. This led to a slightly higher estimate of stem density using the ILRIS derived data (480 stems/Ha for ILRIS compared to 465 stems/Ha from manual measurements) but neither result can be considered more reliable than the other. These data demonstrate that for the 35 m x 35 m plots investigated, there was no difficulty in identifying individual trees within the areas covered by at least a single scan; i.e. within the scan area, no trees have been omitted or erroneously added.

Statistic	Errors	
	Easting (m)	Northing (m)
Avge	-1.5	-1.7
min	-2.3	-2.6
max	0.3	-0.7
std dev	0.3	0.5
n	77	77

Table 3 ILRIS derived tree location offsets compared to POS derived tree locations for the conifer plot 4.

Statistic	Errors	
	Easting (m)	Northing (m)
Avge	2.4	-0.7
min	1.1	-2.7
max	5.0	0.5
std dev	0.9	0.8
n	57	57

Table 4 ILRIS derived tree location offsets compared to manual tape and bearing derived tree locations for the deciduous plot 6.

Within both plots, there was an offset between ILRIS tree locations and those collected manually. Some level of systematic error may be attributable to the fact that the ILRIS data were georegistered using DGPS while the manual tree location data were registered using the POS Backpack system. In addition, the alignment and georegistration processes can easily introduce some 3D warp into the merged scan data as a result of imperfect alignment and erroneous control point definition; both of these problems pose significant challenges within forested environments. However, all ILRIS trees were within 5 m of their ground surveyed location, with the average offsets being around the 2 m level. ILRIS and manual tree locations tended to be closer in the conifer plot 4 than the deciduous plot 6 and this is most likely attributable to increased manual measurement errors in the deciduous plot.

Although locating and counting trees with ILRIS data has been shown to be achievable here, it needs to be borne in mind that prior knowledge of tree numbers and locations was already available for this study. This is an important consideration because in the deciduous plot 6, it was found to be quite difficult to isolate tree stems by a simple vertical slicing procedure. This is illustrated in Figure 12 where it is apparent that understory canopies can overlap with nearby tree stems and make tree separation almost impossible. Fortunately, however, this was not a problem in the conifer plantation (Figure 11), as all tree stems could be easily discriminated. Therefore, ILRIS point cloud data do offer the potential for automated tree number and location estimation but in forest areas other than uniform single tier plantations, this process would require some kind of sophisticated 3D object recognition extraction process.

4.3 Tree Height and DBH

Summary tree height and DBH statistics for the manual and ILRIS methods are presented in Table 5 (plot 4) and Table 6 (plot 6). Regression plots of manual / ILRIS tree height and DBH are presented in Figure 20 (plot 4), Figure 21 (plot 6) and Figure 22 (all tree data). It must be noted that regression plots are perhaps not the most appropriate form of illustration for the manual/ILRIS relationship within the conifer plot 4 (Figure 20) due to the very limited range of values experienced within this plantation type environment. However, Figure 20 is included for consistency of data presentation; when considering the validity of ILRIS for tree height and DBH estimation in a plantation context, it is more appropriate to evaluate the numerical statistics provided in Table 5.

Plot 4 conifer	Tree Height (m)		DBH (m)	
	ILRIS	*Maual*	*ILRIS*	*Maual*
Mean	22.1	23.6	0.26	0.27
Standard Error	0.14	0.12	0.01	0.00
Median	22.1	23.6	0.27	0.27
Standard Deviation	1.2	1.0	0.06	0.03
Sample Variance	1.55	1.10	0.00	0.00
Kurtosis	-0.69	4.22	2.10	0.40
Skewness	-0.29	-1.02	-0.78	0.29
Range	5.1	6.5	0.31	0.18
Minimum	19.3	19.6	0.08	0.20
Maximum	24.3	26.1	0.39	0.37
Sum	1676	1911	18.3	21.6
Count	76	81	70	81
Conf Level (95%)	0.28	0.23	0.01	0.01

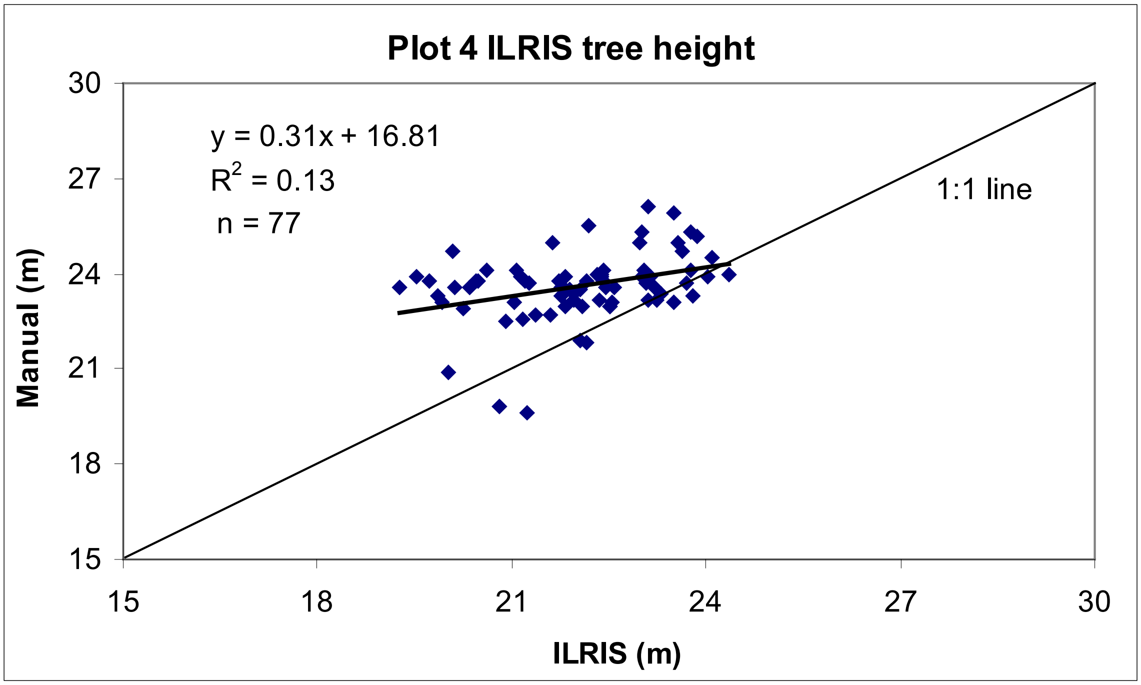
Table 5 Tree height and DBH statistics for ILRIS derived and manual measurements for the conifer plot 4.

Plot 6 deciduous	Tree Height (m)		DBH (m)	
	ILRIS	*Maual*	*ILRIS*	*Maual*
Mean	17.9	19.4	0.25	0.24
Standard Error	0.86	1.04	0.02	0.02
Median	20.6	22.3	0.25	0.24
Standard Deviation	6.4	7.8	0.13	0.14
Sample Variance	41.1	61.4	0.02	0.02
Kurtosis	-0.02	-0.78	-0.38	-0.23
Skewness	-1.13	-0.76	0.37	0.49
Range	21.5	28.1	0.53	0.60
Minimum	2.8	2.7	0.04	0.02
Maximum	24.3	30.8	0.57	0.62
Sum	1001	1105	12.6	13.8
Count	56	57	51	57
Conf Level (95%)	1.72	2.08	0.04	0.04

Table 6 Tree height and DBH statistics for ILRIS derived and manual measurements for the deciduous plot 6.

From Tables 5 and 6, there appears to be reasonable correspondence between manual and ILRIS tree height and DBH measures in both plots. For all of the mean values presented, the greatest difference between ILRIS and manual measurement is < 8%. For DBH, there appears no systematic tendency for ILRIS to under- or over-estimate the ground-truth value. For tree height, however, a tendency for ILRIS to under-estimate the ground-truth value is observed in both plots. This result illustrates the influence of canopy shadowing, which reduces the laser point density at tree top level (see Figures 13 and 14 for examples). For both plots, this average tree height under-estimate is 1.5 m despite very different canopy structures and suggests that the under-estimate may be somewhat systematic.

Most of the error (whether it be with ILRIS or manual measurements) occurs as a result of not being able to clearly see the top of the highest trees within each plot; i.e. the tops of the shorter trees tend to be more visible than the tops of the taller trees. This can potentially lead to ILRIS under-estimations due to canopy shadowing, or it could also lead to manual over-estimations of tree height for the same reason. It is likely that any systematic ILRIS measurement under-estimation would be a function of canopy structure, height and density and could potentially be corrected for. The nature of such an offset, however, would require that more data be collected over different forest types so that certain questions could be addressed; e.g. can the plot level under-estimate be defined as a simple offset or should it change as a function of other measurable parameters? These questions cannot be answered here, but it is likely that with further research, any systematic component of this under-estimation error could be accounted for in future plot level ILRIS tree height estimates.



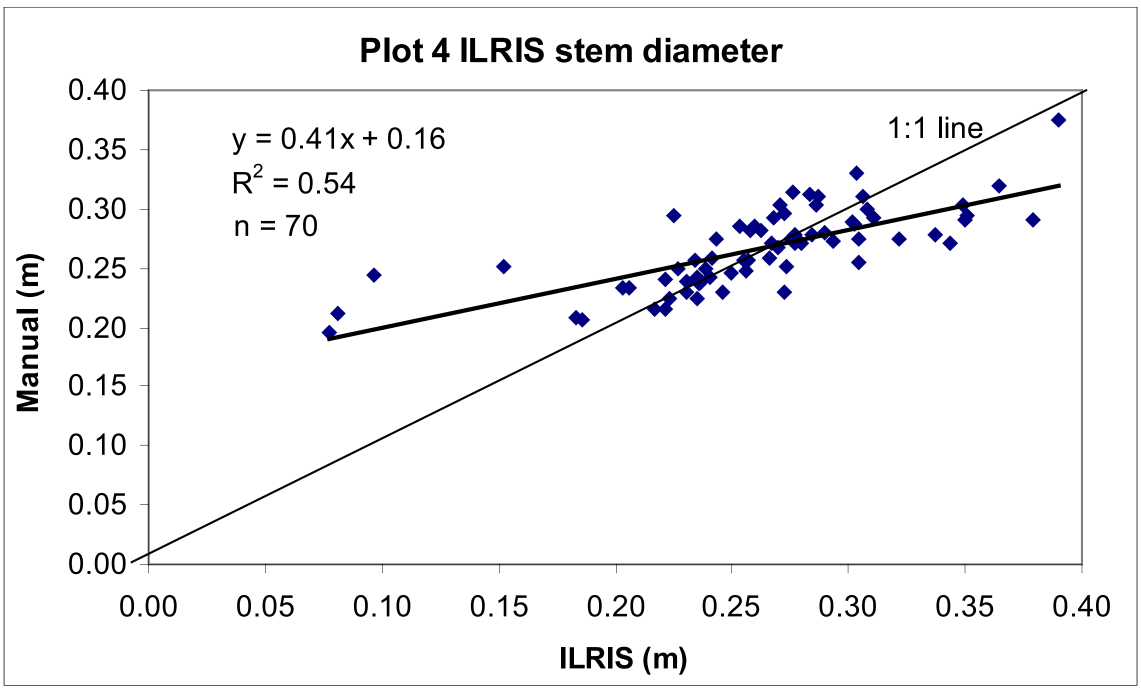
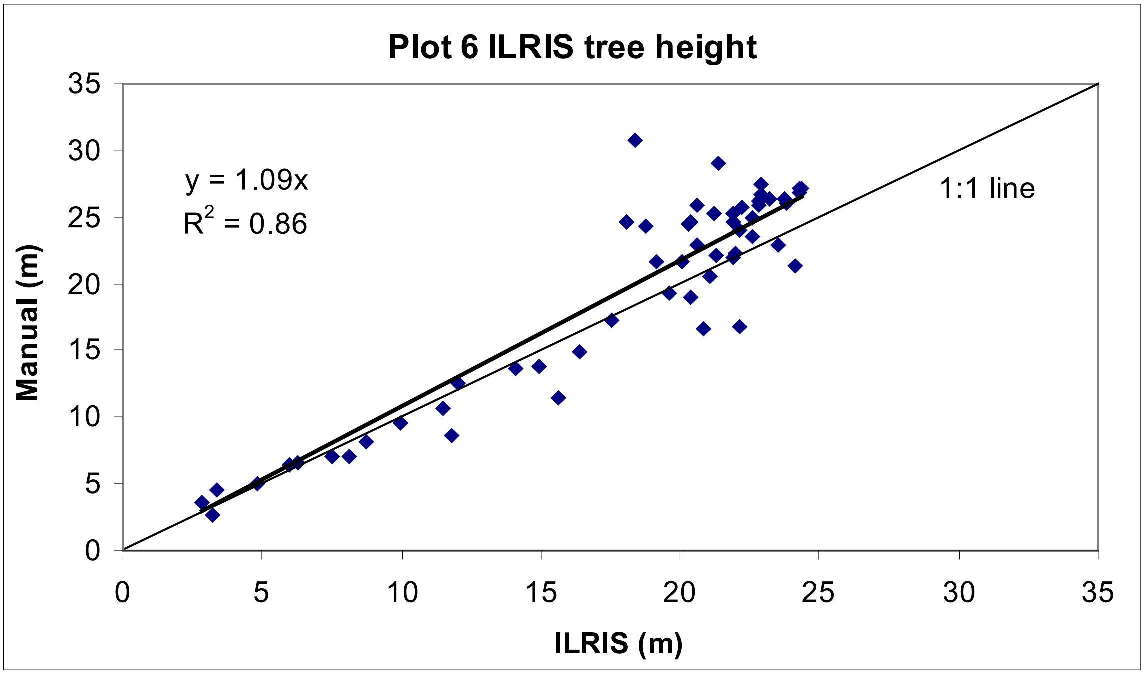


Figure 20 Regression plots of manual/ILRIS tree height and DBH measurements for conifer plot 4.

Although the r^2 values for both tree height and DBH plots in Figure 20 are relatively low, both parameters are clustered very close to the 1:1 line. ILRIS DBH shows no tendency for under- or over-estimation but ILRIS tree height shows a greater range than is evident in the ground-truth heights.



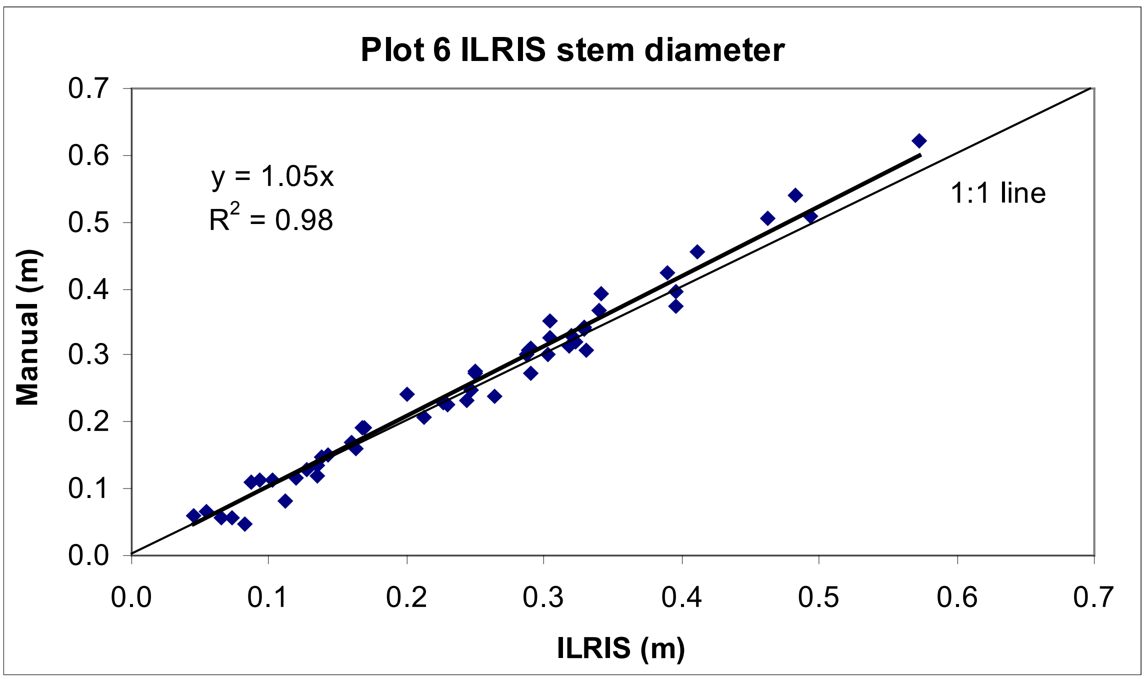
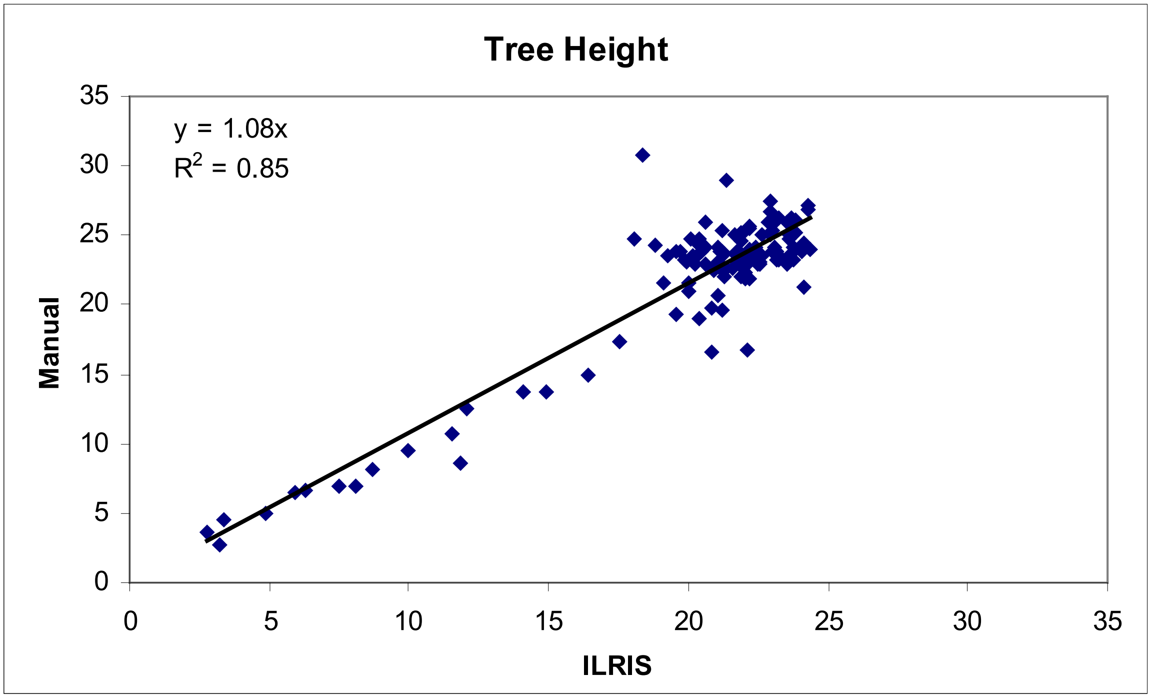


Figure 21 Regression plots of manual/ILRIS height and DBH measurements for deciduous plot 6.

DBH shows a good linear relationship between ILRIS and manual measurements for the deciduous plot that is very close to the 1:1 line (Figure 21). The tree height relationship between ILRIS and manual measurements is close to the 1:1 line up until the tallest trees are encountered. At the level of the tallest tees, ILRIS demonstrates a tendency to under-estimate the manual height measurement. However, given the difficulty of making accurate manual measurements in this part of the canopy, this result does not necessarily *prove* any inferiority of the ILRIS data.



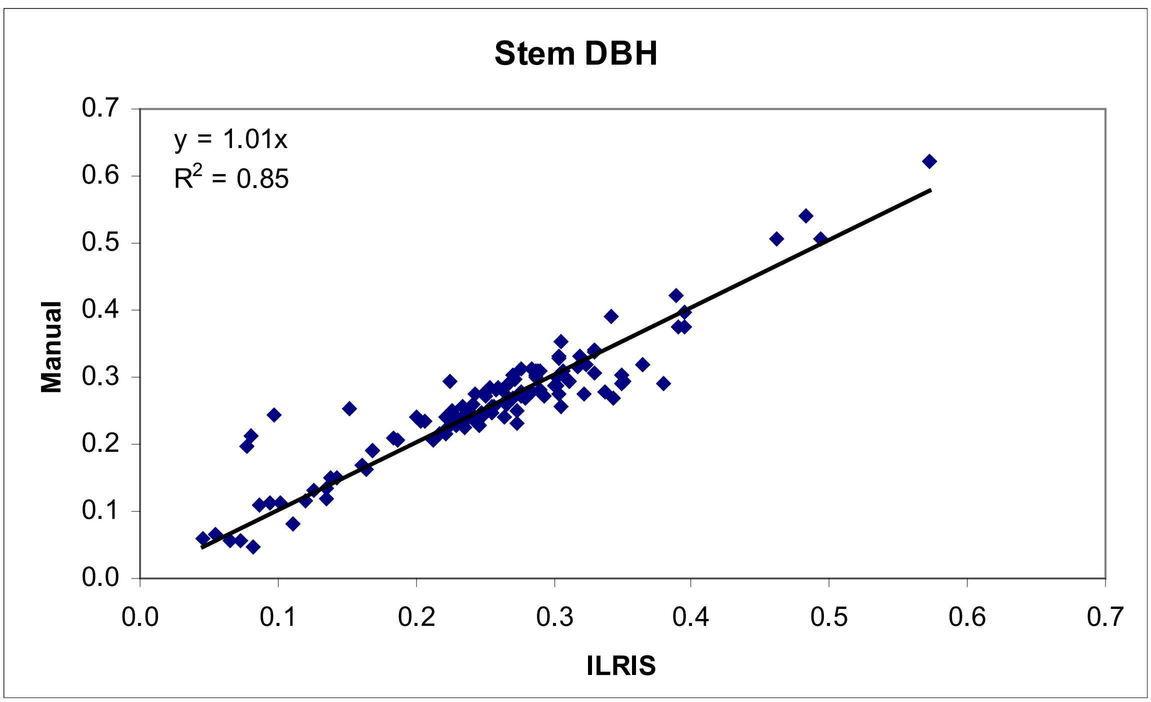


Figure 22 Regression plots of manual/ILRIS tree height and DBH measurements for both plots.

4.4 Tree Crown Diameter

Tree crown diameter was assessed from the ILRIS point cloud data from three trees only. Therefore, no statistically significant results can be presented. However, it can be seen in Table 7 that values extracted from the ILRIS data are in the same range as those derived manually in the field. Both the manual and ILRIS measurements are subjective measures and there is no way of knowing which measure would be more accurate; i.e. the "ground-truth" measure in this case, can hardly be considered a highly accurate or objective measure of the "true" crown diameters. This being the case, it is supposed that ILRIS data may actually provide a means of estimating crown diameter that is at least as good as manual field measures. However, there are insufficient data here to prove or disprove this supposition and so it must remain an open topic.

	ILRIS			Manual		
Tree ID	NS	EW	Avg	NS	EW	Avg
106	4.9	3.9	4.4	4.3	3.9	4.1
107	4.5	3.3	3.9	4.2	3.6	4
108	2.7	2.5	2.6	4.3	3.4	3.8

Table 7 ILRIS and manual tree crown diameter measurements.

4.5 Forest Mensuration Statistics

From the above measures of plot and scan cover area, average tree heights and DBH, it was possible to generate a suite of forest mensuration statistics from both the ground truth and ILRIS derived plot level data. These summaries are presented in Table 8 (plot 4) and Table 9 (plot 6). Most of these metrics have been discussed in previous sections but are included in the tables here for completeness. Of particular interest here, are the "bottom line" estimates of gross total tree volume and merchantable volume derived using appropriate allometric equations and either the ILRIS or manual ground-truth data.

All ILRIS derived estimates of volume are within 7% of those calculated from manual ground-truth measurements. For the conifer plot 4, the ILRIS data leads to a slight under-estimation of both gross and merchantable volume and this is attributable to slight under-estimations of both DBH and tree height. However, for the deciduous plot 6 the ILRIS data slightly over-estimates gross and merchantable volume, and this is largely due to a slight over-estimate of stem density. Therefore, there is no systematic tendency for ILRIS data to either over- or under-estimate plot level tree volumes. In addition, when it is considered that manual measures of stem density, DBH and height are not necessarily objective or highly accurate measurements themselves, there is no way of knowing which data source (ILRIS or manual) provides the best estimate of volume. Further, the allometric equations used are purely empirical and in many operational situations are not derived for the plots to which they are being applied. Therefore, there is potentially a high margin of error in the volume estimates, regardless of which data source is used.

Plot 4 conifer metrics	Manual	ILRIS
Area (Ha)	0.123	0.117
Mean DBH (cm)	26.7	26.2
Total basal area (m^2/Ha)	37.4	37.2
Mean tree height (m)	23.6	22.1
Max tree height (m)	26.1	24.3
Lorey's tree height (m)	23.7	22.3
Stem density (#/Ha)	661	661
Gross total tree volume (m^3)	107.5	100.8
Merchantable volume (m^3)	103.7	97.1

Table 8 Summary manual and ILRIS mensuration statistics for conifer plot 4.

Plot 6 deciduous metrics	Manual	ILRIS
Area (Ha)	0.123	0.119
Mean DBH (cm)	24.2	24.7
Total basal area (m^2/Ha)	28.5	28.3
Mean tree height (m)	19.4	17.9
Max tree height (m)	30.8	24.3
Lorey's tree height (m)	24.7	21.3
Stem density (#/Ha)	465	480
Gross total tree volume (m^3)	53.3	56.3
Merchantable volume (m^3)	48.0	50.7

Table 9 Summary manual and ILRIS mensuration statistics for deciduous plot 6.

4.6 Vertical Biomass Profiling

Although ILRIS provides directly digital information of the 3D distribution of biomass within a plot, it was outside the scope of this report to thoroughly research methods that could quantify or map this distribution. However, a vertical profile of laser points per elevation band was created to illustrate that overall vertical profiles of something analogous to biomass could easily be generated. The vertical profile illustrated in Figure 23 is not actual biomass distribution but given that the ILRIS sample point density throughout the plot can theoretically be calculated, it is conceivable that such a profile could be converted to an estimate of the volume of space occupied by vegetation. However, biases associated with scan angle and canopy shadowing would need to be addressed before vertical point density distributions could be converted to actual canopy structure and biomass. These are problems that can be relatively easily overcome with some simple physical laser scan attribute functions and spatial probability distribution modelling. This work is currently ongoing.

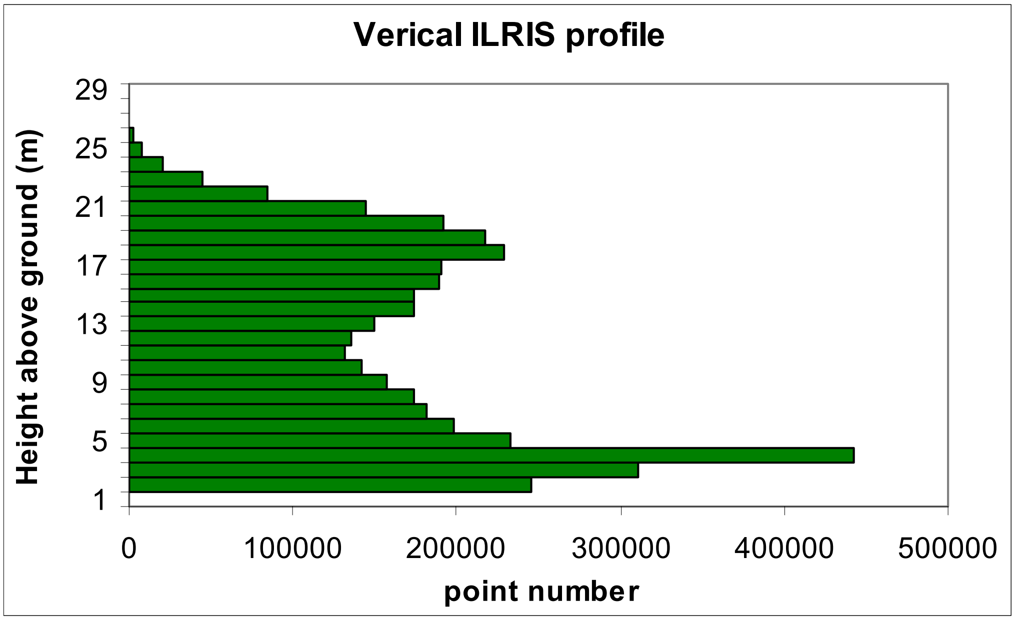


Figure 23 Vertical profile of ILRIS laser points within each elevation band above an arbitrary height

4.7 Single Scan Test Data

Tree point clouds extracted from the single scan data collected in Southern Ireland are illustrated in Figure 23. The horizontal area of the single scan that was analysed was a little over 30 m deep, with front and back widths of approximately 15 m and 30 m, respectively. It took less than 15 minutes to collect the scan data and between two and three hours to manually extract all 25 trees from the entire scan, measure tree heights and DBH, and generate plot level statistics. Individual tree level data are presented in Table 10 and a plot level summary is provided in Table 11. With appropriate local allometric equations, these data could be easily converted into estimates of biomass and merchantable timber volume. When automation routines are available, the time to process the data through to plot level statistics and volume estimates will be drastically reduced, and will certainly be faster than current traditional techniques.

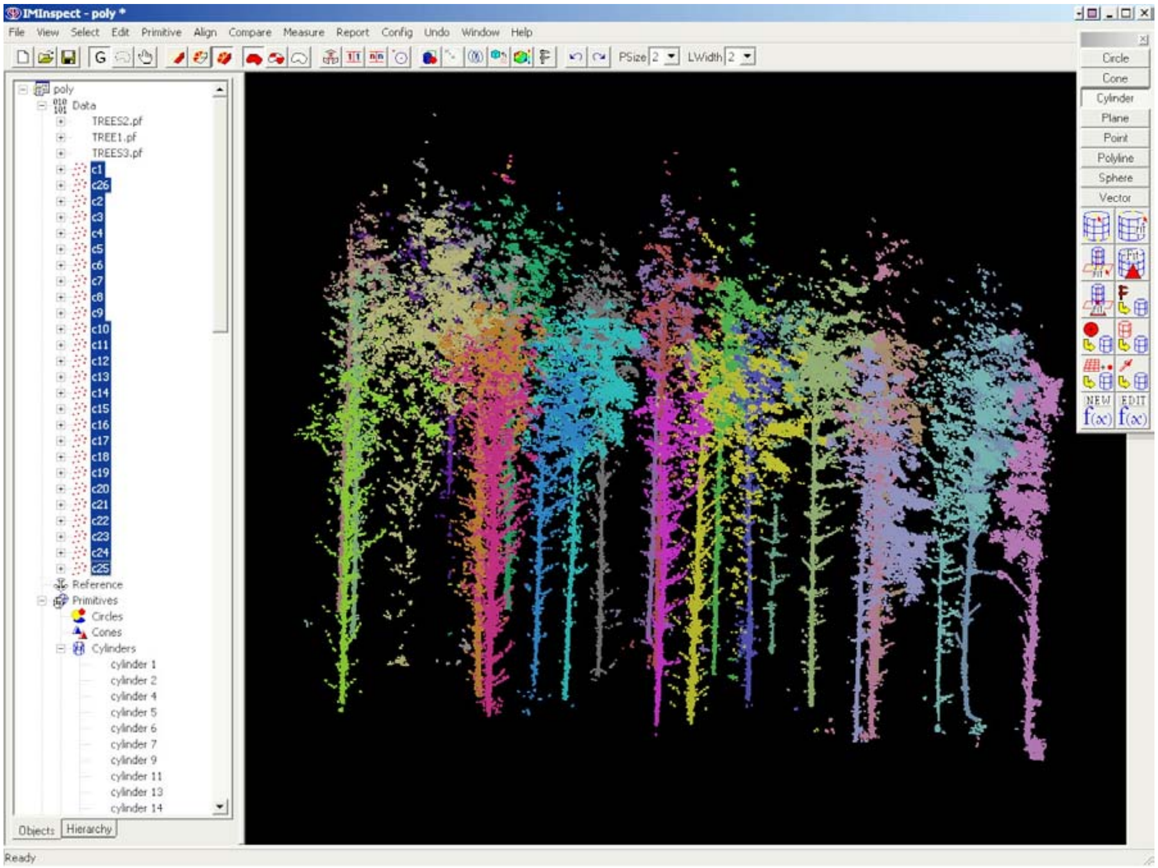


Figure 24 Oblique view of manually extracted tree point clouds from single scan data collected within a sitka spruce plot in Southern Ireland.

There is high confidence that all trees were visible within the single scan. However, many of the trees extracted from the point cloud only contained partial data. For example, DBH for all trees could not be measured due to obstacle shadowing (see Table 10). This did not cause a problem for plot level DBH estimation though because 17 out of 25 trees gives a sample population of almost 70% and thus should provide a reasonable estimate for the entire plot population. Although these data have not been compared with ground-truth, they do illustrate that ILRIS can be used to generate forest mensuration statistics relatively quickly and objectively compared to more traditional techniques.

Tree ID	Top ht (m)	DBH (m)	X co-ord	Y co-ord
1	20.07	0.33	164.36	53.05
2	20.53	0.35	172.60	46.17
3	23.67		171.85	51.83
4	22.82	0.37	177.21	49.00
5	25.58	0.39	171.67	54.73
6	22.57	0.29	175.47	56.24
7	20.26	0.30	180.15	52.49
8	18.98		179.41	56.16
9	22.11	0.20	180.87	64.09
10	21.72		173.58	65.62
11	25.71	0.33	177.67	64.42
12	25.54		176.32	61.66
13	22.63	0.35	172.76	59.92
14	25.05	0.34	167.46	61.78
15	22.56	0.33	161.16	62.20
16	21.96		170.79	65.39
17	26.01		160.72	69.41
18	27.82	0.36	161.42	72.21
19	20.36	0.30	156.57	72.80
20	28.28		162.47	72.04
21	20.99	0.43	181.46	71.02
22	19.30	0.40	181.54	72.59
23	25.85		179.88	75.78
24	21.00	0.39	178.85	77.04
25	18.97	0.38	176.18	74.83
Avge	**22.81**	**0.34**		
min	**18.97**	**0.20**		
max	**28.28**	**0.43**		
std dev	**2.74**	**0.05**		
Number	**25**	**17**		

Table 10 Raw ILRIS derived tree level height and DBH statistics for the Irish sitka spruce plot.

Forest menuration data	
Area (Ha)	**0.07**
Mean DBH (m)	**0.32**
Total basal area (m^2/Ha)	**1.4**
Mean tree height	**22.8**
Max tree height	**28.3**
Lorey's tree height (m)	**22.2**
Stem density (#/Ha)	**357**

Table 11 Plot level forest mensuration summary statistics derived from ILRIS for sitka spruce plot.

5 Potential ILRIS Scan Configurations

5.1 Scanning Limitations

For the analysis and data presented in this report, it has been noted that the scan configuration around each plot was not optimal for the task at hand. Particularly, the spacing of the ILRIS base locations around the plots and the distances out from the plots were irregular, leading to an uneven distribution of points within the plots. This was mainly because the test performed had not been carried out before and none of the field personnel had any experience with this kind of LiDAR forestry data collection. However, after viewing all the scan data and resultant tree level statistics it is apparent that improvements to the data collection methodology can be made.

In addition to uneven scan sampling throughout the plots, another obstacle on the way to tree data extraction was accurate alignment of multiple scans. The high density of similar looking features in each plot made finding suitable “tie points” in adjacent scans very difficult and time consuming. There are two solutions to this problem:

1. Only use single scan data and avoid the need to align the scans;
2. Place highly visible control markers at strategic positions throughout the plot being scanned.

It has been demonstrated that forest mensuration statistics can be readily generated from single scan data and the likelihood of omitting any trees is quite small. However, shadowing is a significant problem when looking at single scan data alone and although mensuration statistics were generated for the Irish sitka spruce plot discussed in section 4.7, the lack of manual tree metric data for this plot precluded the possibility of evaluating the accuracy of the single scan data. This is a task that still needs to be performed and so, for the time being, the need to align multiple scans and place good control markers throughout the plot must be considered in optimal scan configuration options. Therefore, in subsequent discussions of optimal scan sampling, single, dual, tri and central scan configurations will be considered.

For the purpose of establishing an optimal scan configuration, only ILRIS base location and plot dimensions will be considered here. Optimal scan rates and sample point density will not be considered but in operational use will likely be chosen based on the amount of time available for data collection and the volume of data the end-user wishes to or can work with. When designing an optimal scan sampling configuration, the limitations of the instrument and site being sampled need to be considered. There are four major limitations to plot dimension and ILRIS base location set up:

1) There must be enough tree data for results to be meaningful; i.e. statistically significant;
2) Physical restrictions are imposed by the scanning properties of the sensor:
    a. 40^{o} horizontal and vertical field of view;
    b. a need to be able to see the ground in any single scan (this restriction was stated by the manufacturer but can probably be overcome);
3) Point cloud data must be collected over the full height range of the trees;
4) Shadowing can cause a loss of data if large obstacles are near the front of the plot (more of an issue in dense stands and in the upper canopy).

The first limitation is codependent on sample plot size and stem density; i.e. for a dense stand of trees, the sample plot size containing a sufficient number of trees to provide statistically significant results will be smaller than for a stand of widely spaced trees. However, it should also be considered that although a dense stand only requires a small plot size to contain a high number of trees, this same plot will likely be more susceptible to obstacle shadow problems than in the less dense stand. The net result of this effect is that for the same size plot, a greater quantity of tree data would be available in the dense stand but the data from the more open stand would be of a higher quality. Field tests would be required to test and quantify the significance of these opposing effects on mensuration statistics. For the sake of designing the optimal scan configuration for a plot, it would be prudent to aim to sample more trees than are necessary for significance.

The second limitation is hardware related. A 40^{o} field of view is a serious restriction for forestry data collection of the type described in this report. A wider field of view would result in dramatic improvements, in plot sampling capability. Other manufacturers do make 3D laser imagers with a wider field of view than 40^{o} but they were unavailable for test in this study. The ILRIS field of view can be artificially increased by rotating the sensor box upwards or sideways. However, this is problematic, as the mount for the ILRIS does not allow for simple rotations, and there is no facility for monitoring the amount of instrument rotation; i.e. horizontal azimuth and vertical tilt cannot currently be measured. In addition, it has been stated the ground should be visible in all scans to assist with alignment. This requirement restricts the upward rotation of the sensor. With further field trials and an improved mounting bracket these restrictions could potentially be overcome.

The third limitation controls the minimum distance between the plot edge and the ILRIS base location. The base location needs to be far enough away from the plot so that where the scan meets the plot boundary, the top edge is at the elevation of the tallest tree and the bottom edge is at ground level. This ensures that the full height of the plot is represented within the scan range.

The fourth limitation is more of a consideration during field operations; i.e. when actually setting up an ILRIS survey, the operator needs to ensure that obstacles in between the ILRIS and the plot to be surveyed are minimized. However, this restriction may also dictate the type of survey to be conducted. For example, all other criteria may suggest that a single scan would be sufficient for a particular plot, but the presence of one or more large obstacles within or near to the plot may dictate that more than one scan is needed to avoid the effects of scan shadow.

Bearing these limitations in mind, various scan configurations have been considered. In all of the examples presented below it is assumed that the plot to be sampled is within a conifer plantation with a maximum tree height of approximately 25 m and an approximate stem density of 450 stems/Ha.

5.2 Single Scan

A single scan design is the simplest scenario to set up. Figure 25 illustrates the basic geometric configuration. For a single scan, the planimetric shape of the optimal plot will approximate a four-sided truncated triangle with the width of the side nearest the ILRIS base having a dimension *W.F.*, a depth *D*, and a width at the far side of the plot of *W.B.* (see Figure 25). The depth of the plot would be adjusted to meet the minimum plot size criteria for a significant number of trees in the sample. In order to set up this plot sample, only two quantities need to be calculated:

1) X = the distance of the ILRIS base from the front edge of the plot;
2) α = the angle of vertical inclination above the local ground surface (if the ground surface is flat, this would be the angle above horizontal).

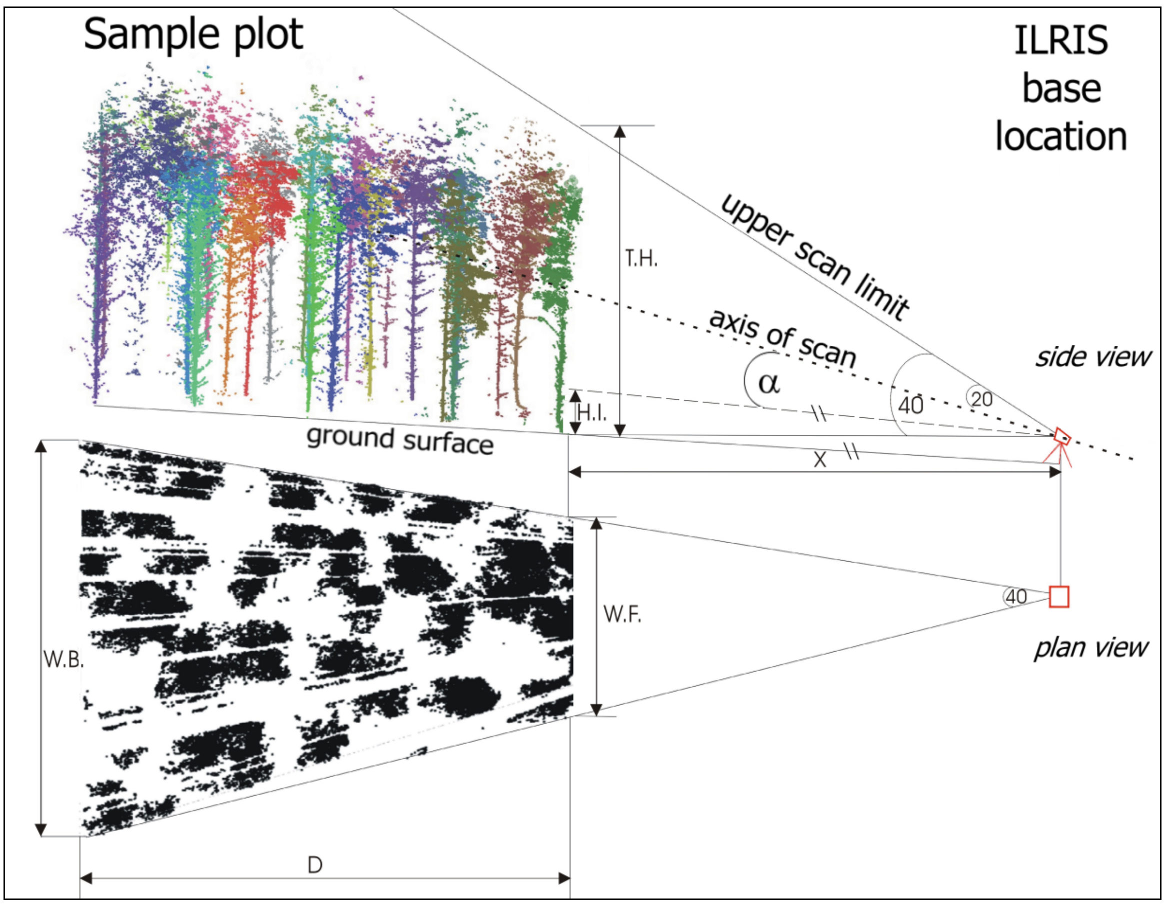


Figure 25 Single scan setup. (Point cloud data illustrated were collected for the sitka spruce plot discussed in section 4.7). Nb. Ground surface is not quite horizontal in upper side view of diagram.

X and α can be calculated based on knowledge of the instrument height (*H.I.*) and an estimate of the maximum plot tree height (*T.H.*). X and α are related to one another in the following way (assuming the ground is relatively flat):

$$X \geq H.I. / \tan (20^o - \alpha) \qquad (5)$$

And:

$$X \geq (T.H. - H.I.) / \tan (20^o + \alpha) \qquad (6)$$

For expediency sake, *H.I.* may be considered negligible compared to *T.H.*, and in this case the maximum value for X can be obtained from an estimate of *T.H.* alone:

$$X \leq T.H. / \tan 40^o \qquad (7)$$

For the estimated maximum tree height of 25 m, this gives a maximum X value of 29.8 m. By accounting for an *H.I.* value of 1.5 m, X becomes 25.5 m and α becomes 16.6^o above the ground slope; however, this was slightly more complex to calculate and for operational purposes it would be sufficient to assume that X should have a value that lies somewhere between the tree height and the maximum value as defined in equation 7, above.

For an X value of 25.5, *W.F.* becomes 18.6 m. If we assume a plot depth D that is slightly greater than *W.F.* of 20 m, then *W.B*. becomes 33.1 m. A plot with these dimensions has an area of 662 m^2 or 0.066 Ha, and for a stem density of 450 stems/Ha, this plot would contain approximately 30 trees. The criteria for significance would change with the level of heterogeneity within a plot, but it is probably safe to assume that for most plantations of uniform species and age, a sample size of 30 should provide significant results (provided, of course that most of the trees can be seen and the data extracted are not biased).

For the plot described above, there would be no point within the plot that was more than 55 m away from the ILRIS sensor. Therefore, there is the possibility to effectively "paint" or sample the entire spatial domain within this plot from a single scan. Unfortunately, however, the laser points cannot see through tree trunks and very dense areas of biomass and so shadows can be a problem with a single scan strategy. In addition, the density of laser points at the front of the plot will be three times greater than the density of points at the back of the plot, leading to unrepresentative spatial sampling throughout the 3D plot domain. Bearing these problems in mind, it is important to explore alternative options for setting up and aligning multiple scan configurations that would reduce shadowing and even out the laser point sampling distribution.

5.3 Dual Scan

The simplest form of a dual scan configuration that would even out the sample point density, minimize shadows and allow for a slightly deeper plot would be to line up two ILRIS base locations on opposite sides of the plot (as in Figure 26). The same basic geometric configuration that was applied to the single scan set up above would be used here but the plot would be restricted to the hexagonal overlap area of the two scans. If the same value of 25.5 m is adopted for *X* and a depth *D* of 25 m is adopted to maintain a regular plot size, then *W.C.* = 27.7 m and the overall plot area *A* = 850 m^2 or 0.085 Ha. This area is larger than in the last example as a result of increasing *D*. However, it should be noted that the overall length of the survey site *L* would have be 76 m and this may be restrictive in some dense forested plantations or over sites of undulating terrain.

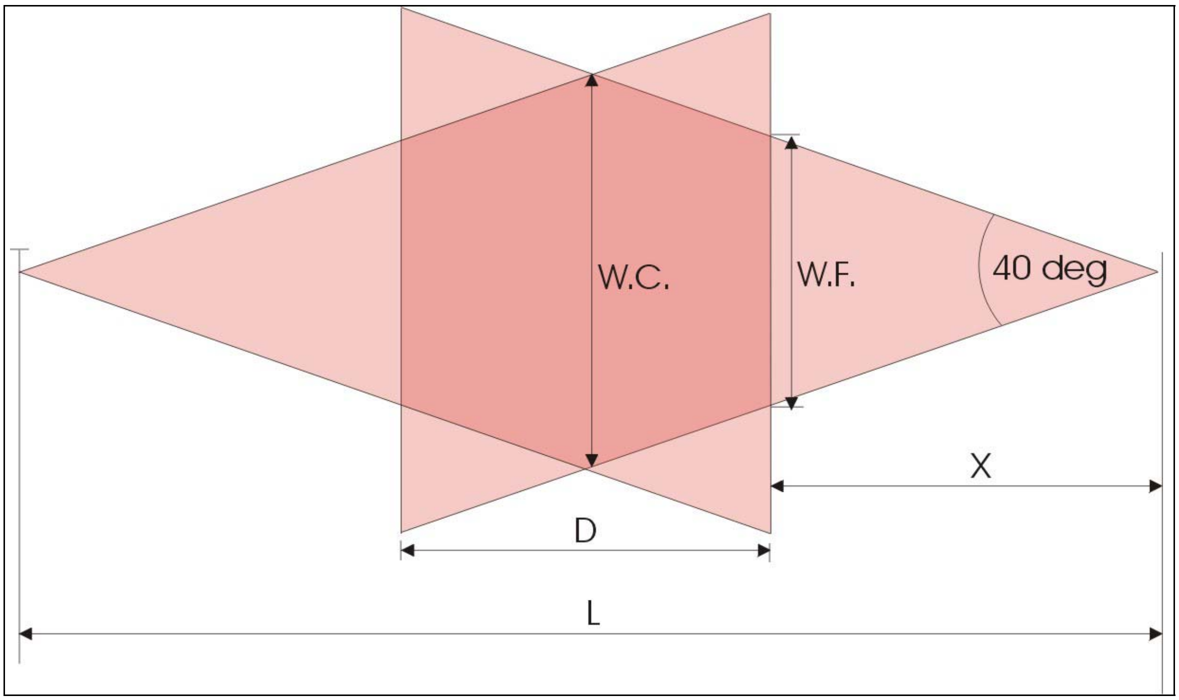


Figure 26 Plan view of simple dual scan configuration to minimise shadows and even out sample point density throughout the plot.

A potential difficulty using this kind of configuration would be the alignment of the scans. There is effectively no overlap between the scans as they are directly opposite one another, and although each scan would see either side of many of the same objects, the current alignment procedure in Polyworks requires the identification of “tie points” in scan overlap areas. However, it is anticipated that alignment procedures will continue to evolve, ultimately facilitating a greater range of scan configurations. In addition, merging two diametrically opposed scans would be aided significantly (as would any alignment within forest areas) by placing several easily identifiable control markers throughout the plot.

5.4 Tri Scan

To avoid potential problems associated with aligning diametrically opposed scans, a multiple overlapping scan configuration must be adopted. With three ILRIS base locations it is possible to ensure sufficient overlap for alignment, maintain an even sample point density and minimize obstacle shadows by evenly spacing the ILRIS around a hexagonal sample plot (see Figure 27). Each base location would be located at the corners of an equilateral triangle and pointed into the centre. *X* would still be used to define the distance to the plot, and depth could be defined as a distance *B* into the centre of the plot. Given that *X* now defines a distance to a plot corner (see Figure 27) rather than a full side, the value for *X* is less critical and it would probably be sufficient to use *H.T.* as a first approximation of *X*. Therefore, for the example provided below, *X* = 25 m. In order to maintain a total distance from ILRIS to furthest plot location of less than 60 m, a depth to the plot centre *B* of 15 m has been chosen, this results in an overall depth *D* of 28.9 m. (It should be noted that in practice, much greater depths would probably be perfectly acceptable given the number of scans but an attempt is being made here to make the single, dual and tri scan configurations comparable in terms of plot dimension).

The overall area of the plot in Figure 27 would be is 541 m^2 (0.054 Ha) and the number of trees for a 450 stems/Ha plot would be approximately 25. The area is smaller than in either of the two previous examples due to the necessity for all scans to be overlapping. In practice, however, useful data for mensuration or biomass research purposes would likely be accessible outside of the tri-scan overlap area.

From the above example, the scan angle of 40^o results in a large loss of potentially useable sample plot area around the edge of the equilateral triangle that defines the overall site set up. For example, with the exact same site and instrument set up, a scan angle of 60^o, would result in an effective plot area of 1,264 m^2, as opposed to the 541 m^2 available with the 40^o scan. A wider scan, therefore, could lead to smaller overall site dimensions for larger sample plots. This would constitute a significant improvement in capability, as in the example provided, the overall site dimensions (defined by *L1* and *L2* in Figure 27) for this relatively small area of 541 m^2, are approximately 69 m x 60 m. With a 60^o scan, the same plot area could be achieved with *L1* and *L2* dimensions of less than 55 m and 50 m, respectively.

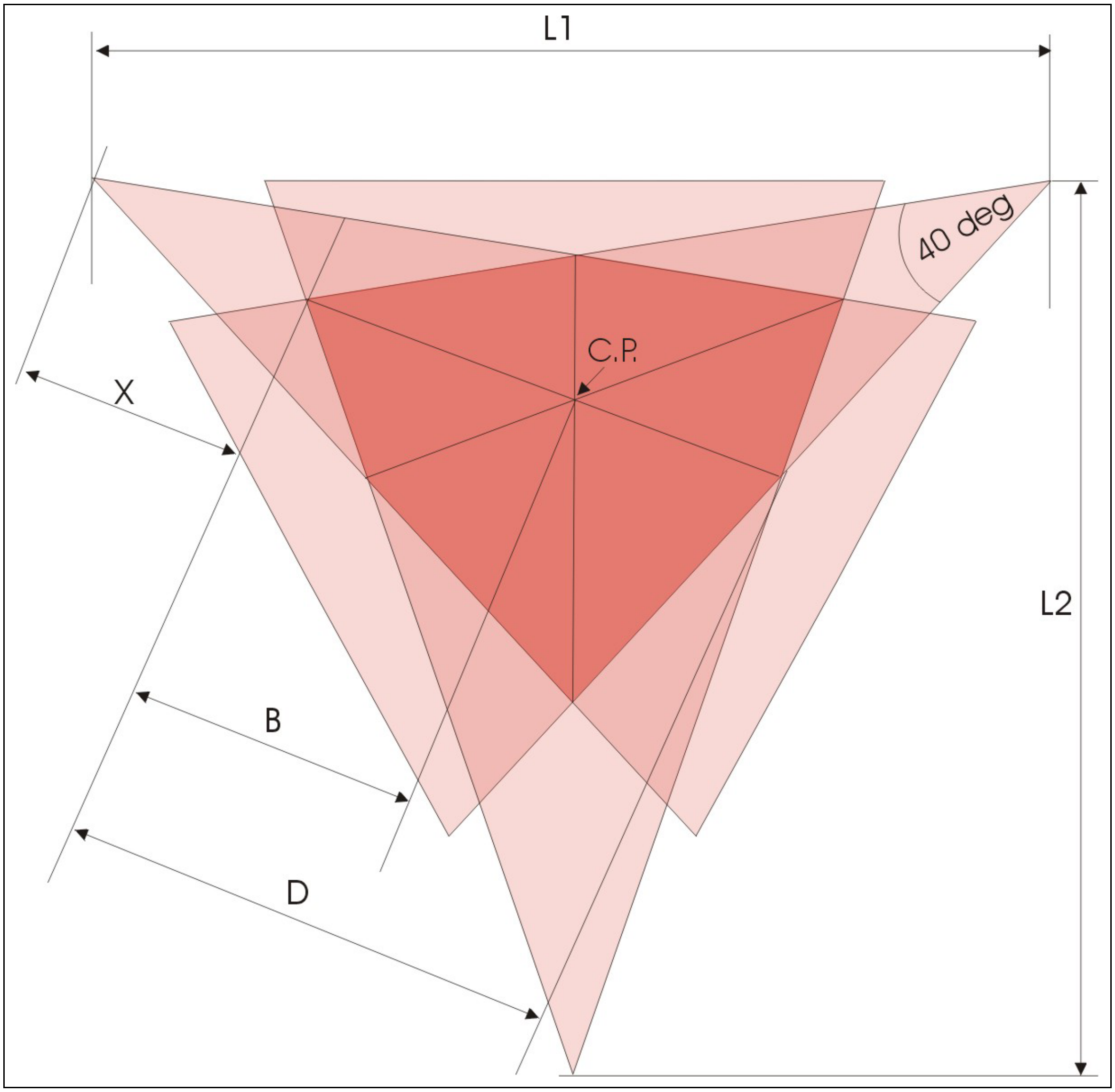


Figure 27 Plan view of tri-scan configuration to facilitate overlap for alignment, minimise shadows and even out sample point density throughout the plot. (Not to scale).

5.5 Centre Scan

The final scan configuration considered here is an adaptation of the single scan set up described above in section 5.2. If nine scans are collected from the same base location, each rotated 40^{o} from the last, then a full circular plot can be sampled. This configuration would not provide any overlap for alignment, and so more scans would be needed if the scans were to be merged. The radius *R* of the plot and effective depth *D* would be determined by the density of the surrounding tree cover and how far the ILRIS could 'see' into the stand or plantation. Using the same *X* and *D* values adopted for the single scan example, this would result in a 'doughnut' shape plot area of approximately 4,460 m^2 (or 0.446 Ha). This type of scan configuration may not be appropriate for operational forest inventory applications but it may be useful for large area biomass and structure assessments for more research oriented projects.

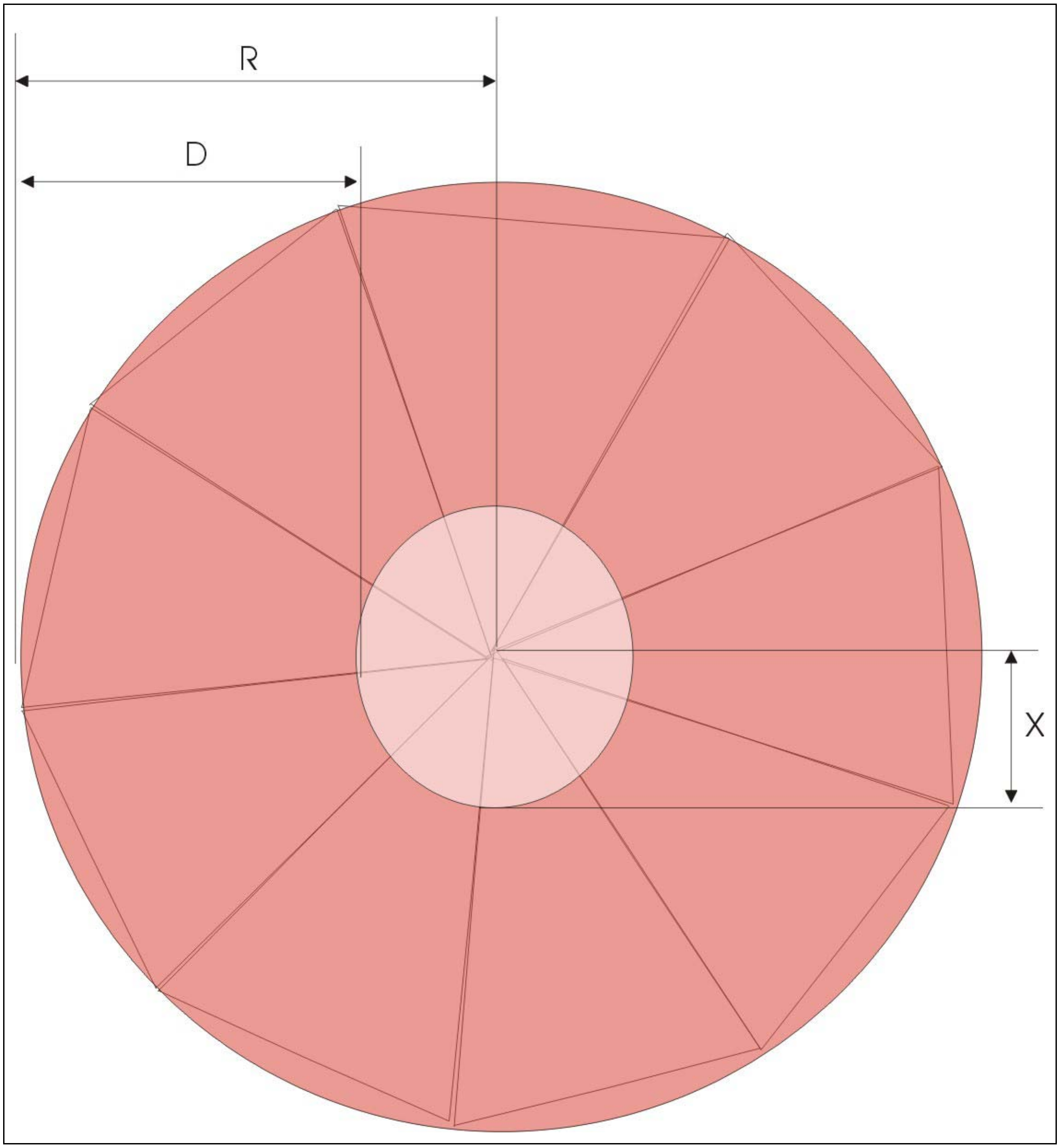


Figure 28 Plan view of centre scan 'doughnut' plot sample configuration.

6 Conclusions

The ILRIS 3D laser imager has proven to be a useful tool for forest metric assessment, with the capability to provide data on tree height, DBH, tree crown diameter and plot volume estimates that are comparable with more traditional techniques. In the sample data collected there was a systematic tendency for ILRIS to under-estimate the average plot level tree height values by approximately 1.5 m compared to manual measurements, and this was likely a function of canopy shadow effects. It is believed that with further investigation, this systematic offset could be either reduced through optimising the scan set up; or empirically corrected for by considering the vertical probability distribution of obtaining laser returns from specific heights within the canopy. DBH measurements extracted from the ILRIS data matched up very well with manual measurements (overall r^2 of 0.98 for 134 trees), despite learning of a better DBH data extraction technique after the analysis had been completed. ILRIS derived gross and merchantable timber volumes for both stands were within 7% of the manual estimates. Given the lack of certainty surrounding some manual measurements and the accuracy of the allometric equations used, there is no way of determining whether the ILRIS based estimates are better or worse than the manual estimates.

Many attributes of the data generated by the ILRIS sensor have not been investigated in this report. For example, although the ability to quantify 3D plot level biomass and structure with ILRIS data has been alluded to here, this task requires more effort to be considered ‘proven’. In addition, no mention has been made of the intensity data that are also provided with the XYZ co-ordinates for each point. It is known that intensity tends to be higher for solid surfaces such as tree trunks rather than leaves, needles and twigs, where laser pulses are more readily split. This knowledge provides the possibility for laser intensity to be used to classify ILRIS point cloud data into leafy and woody biomass classes. These are just two examples of the many areas of ILRIS forest research that are open for development.

Sampling design for forest metric assessment with ILRIS type sensors is another area that probably requires more thought. The data collected for this study were not collected optimally and had more thought been put into the ILRIS base location set up for each plot, then better results may have been obtained. It is known that for this type of forest sampling strategy, the ILRIS base should be sufficiently far from the plot to ensure complete vertical coverage, multiple scans can promote an even point sample distribution and reduce shadow effects, and several easily identifiable targets must be placed within the plot to assist with scan alignment. Some possible sample configurations have been investigated in this report but no firm conclusions can be reached regarding optimal plot set up without further field trials.

Despite the minor questions regarding sample design and data extraction techniques, the speed and objectivity of data collection and extraction available with the ILRIS laser imager are highly desirable attributes. Manual field measurements of every single tree within a plot can be time consuming and are susceptible to subjective interpretation. When automated forest mensuration data extraction routines become available, tree level measurements will be entirely objective (i.e. repeatable) and the time to process the data through to plot level statistics and volume estimates will be significantly faster than traditional mensuration techniques. However, substantial work is needed in developing such automated data extraction techniques.

Laser imaging with ILRIS style instruments offers the ability to recreate many of the forest metrics that are currently measured in traditional forest inventory situations. However, laser imaging also offers the potential to create new data structures and parameters that will enhance our ability to estimate forest structure and biomass. These new levels of information could potentially assist the forest industry improve inventory techniques and overall resource management practices; and also help researchers and government agencies quantify (on a plot by plot basis) forest related biomass CO_2 storages, and ultimately validate vegetation flux models.

References

G.M. Bonnor and S. Magnussen. 1986. *Inventory and growth predictions of the Petawawa Research Forest*. Can. For. Serv., Petawawa National Forestry Institute, Info. Rep. PI-X-66. 41 pages.

Appendix 1 – ILRIS scan settings

Pathways

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Name of 3d image file:	pathway01.i3d
Size of input file:	7978KB
Date of 3d image file:	07/05/02
Time of 3d image file:	13:01:15
System Software Version:	ILRIS-3D 2.2.4
System Serial Number:	SN010130
Input total shots:	747360
Input number of scan lines:	864
Input points per scan line:	865
Output total shots:	667008
Output number of scan lines:	864
Output points per scan line:	772
Range:	19.00 m
Spot Spacing:	14 mm
Range Correction:	750.00 cm
Intensity Correction:	0.00
Range Offset:	-9.15 cm
Pulse Mode:	First Pulse
Calibration Frequency:	100 lines

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Name of 3d image file:	pathway02.i3d
Size of input file:	12081KB
Date of 3d image file:	07/05/02
Time of 3d image file:	13:35:10
System Software Version:	ILRIS-3D 2.2.4
System Serial Number:	SN010130
Input total shots:	1167480
Input number of scan lines:	1080
Input points per scan line:	1081
Output total shots:	1067040
Output number of scan lines:	1080
Output points per scan line:	988
Range:	21.00 m
Spot Spacing:	12 mm
Range Correction:	750.00 cm
Intensity Correction:	0.00
Range Offset:	-9.15 cm
Pulse Mode:	First Pulse
Calibration Frequency:	100 lines

Conifer plot 4

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Name of 3d image file:	130pineplot01.i3d
Size of input file:	12633KB
Date of 3d image file:	07/05/02
Time of 3d image file:	09:14:37
System Software Version:	ILRIS-3D 2.2.4
System Serial Number:	SN010130
Input total shots:	1224000
Input number of scan lines:	1440
Input points per scan line:	850
Output total shots:	1090080
Output number of scan lines:	1440
Output points per scan line:	757
Range:	35.00 m
Spot Spacing:	16 mm
Range Correction:	750.00 cm
Intensity Correction:	0.00
Range Offset:	-9.15 cm
Pulse Mode:	First Pulse
Calibration Frequency:	100 lines
Number of Outliers Removed:	28551

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Name of 3d image file:	130pineplot02.i3d
Size of input file:	7978KB
Date of 3d image file:	07/05/02
Time of 3d image file:	09:30:31
System Software Version:	ILRIS-3D 2.2.4
System Serial Number:	SN010130
Input total shots:	747360
Input number of scan lines:	864
Input points per scan line:	865
Output total shots:	667008
Output number of scan lines:	864
Output points per scan line:	772
Range:	33.00 m
Spot Spacing:	25 mm
Range Correction:	750.00 cm
Intensity Correction:	0.00
Range Offset:	-9.15 cm
Pulse Mode:	First Pulse
Calibration Frequency:	100 lines
Number of Outliers Removed:	31358

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Name of 3d image file:	pineplot03.i3d
Size of input file:	12081KB
Date of 3d image file:	07/05/02
Time of 3d image file:	10:15:42
System Software Version:	ILRIS-3D 2.2.4
System Serial Number:	SN010130
Input total shots:	1167480
Input number of scan lines:	1080
Input points per scan line:	1081
Output total shots:	1067040
Output number of scan lines:	1080
Output points per scan line:	988
Range:	34.00 m
Spot Spacing:	20 mm
Range Correction:	750.00 cm
Intensity Correction:	0.00
Range Offset:	-9.15 cm
Pulse Mode:	Last Pulse
Calibration Frequency:	100 lines
Number of Outliers Removed:	87541

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Name of 3d image file:	pineplot05a.i3d
Size of input file:	7978KB
Date of 3d image file:	07/05/02
Time of 3d image file:	10:52:03
System Software Version:	ILRIS-3D 2.2.4
System Serial Number:	SN010130
Input total shots:	747360
Input number of scan lines:	864
Input points per scan line:	865
Output total shots:	671328
Output number of scan lines:	864
Output points per scan line:	777
Range:	35.00 m
Spot Spacing:	26 mm
Range Correction:	750.00 cm
Intensity Correction:	0.00
Range Offset:	-9.15 cm
Pulse Mode:	Last Pulse
Calibration Frequency:	100 lines
Number of Outliers Removed:	163788

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Name of 3d image file:	pineplot06.i3d
Size of input file:	7978KB
Date of 3d image file:	07/05/02
Time of 3d image file:	11:39:12
System Software Version:	ILRIS-3D 2.2.4
System Serial Number:	SN010130
Input total shots:	747360
Input number of scan lines:	864
Input points per scan line:	865
Output total shots:	667008
Output number of scan lines:	864
Output points per scan line:	772
Range:	33.00 m
Spot Spacing:	25 mm
Range Correction:	750.00 cm
Intensity Correction:	0.00
Range Offset:	-9.15 cm
Pulse Mode:	First Pulse
Calibration Frequency:	100 lines
Number of Outliers Removed:	33002

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Name of 3d image file:	pineplot08.i3d
Size of input file:	7978KB
Date of 3d image file:	07/05/02
Time of 3d image file:	12:21:29
System Software Version:	ILRIS-3D 2.2.4
System Serial Number:	SN010130
Input total shots:	747360
Input number of scan lines:	864
Input points per scan line:	865
Output total shots:	667008
Output number of scan lines:	864
Output points per scan line:	772
Range:	34.00 m
Spot Spacing:	25 mm
Range Correction:	750.00 cm
Intensity Correction:	0.00
Range Offset:	-9.15 cm
Pulse Mode:	First Pulse
Calibration Frequency:	100 lines
Number of Outliers Removed:	33442

Deciduous plot 6

Name of 3d image file:	FOREST01.I3D
Size of input file:	12081KB
Date of 3d image file:	07/05/02
Time of 3d image file:	14:04:02
System Software Version:	ILRIS-3D 2.2.4
System Serial Number:	SN010130
Input total shots:	1167480
Input number of scan lines:	1080
Input points per scan line:	1081
Output total shots:	1067040
Output number of scan lines:	1080
Output points per scan line:	988
Range:	23.00 m
Spot Spacing:	14 mm
Range Correction:	750.00 cm
Intensity Correction:	0.00
Range Offset:	-9.15 cm
Pulse Mode:	First Pulse
Calibration Frequency:	100 lines

Name of 3d image file:	FOREST03.I3D
Size of input file:	12081KB
Date of 3d image file:	07/05/02
Time of 3d image file:	14:21:57
System Software Version:	ILRIS-3D 2.2.4
System Serial Number:	SN010130
Input total shots:	1167480
Input number of scan lines:	1080
Input points per scan line:	1081
Output total shots:	1067040
Output number of scan lines:	1080
Output points per scan line:	988
Range:	28.00 m
Spot Spacing:	17 mm
Range Correction:	750.00 cm
Intensity Correction:	0.00
Range Offset:	-9.15 cm
Pulse Mode:	First Pulse
Calibration Frequency:	100 lines

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Name of 3d image file:	FOREST05.I3D
Size of input file:	7978KB
Date of 3d image file:	07/05/02
Time of 3d image file:	14:37:38
System Software Version:	ILRIS-3D 2.2.4
System Serial Number:	SN010130
Input total shots:	747360
Input number of scan lines:	864
Input points per scan line:	865
Output total shots:	710208
Output number of scan lines:	864
Output points per scan line:	822
Range:	23.00 m
Spot Spacing:	17 mm
Range Correction:	750.00 cm
Intensity Correction:	0.00
Range Offset:	-9.15 cm
Pulse Mode:	First Pulse
Calibration Frequency:	100 lines
Number of Outliers Removed:	22219

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Name of 3d image file:	FOREST07.I3D
Size of input file:	12081KB
Date of 3d image file:	07/05/02
Time of 3d image file:	15:16:28
System Software Version:	ILRIS-3D 2.2.4
System Serial Number:	SN010130
Input total shots:	1167480
Input number of scan lines:	1080
Input points per scan line:	1081
Output total shots:	1122120
Output number of scan lines:	1080
Output points per scan line:	1039
Range:	25.00 m
Spot Spacing:	15 mm
Range Correction:	750.00 cm
Intensity Correction:	0.00
Range Offset:	-9.15 cm
Pulse Mode:	First Pulse
Calibration Frequency:	100 lines
Number of Outliers Removed:	27916

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Name of 3d image file:	FOREST09.I3D
Size of input file:	7978KB
Date of 3d image file:	07/05/02
Time of 3d image file:	15:45:23
System Software Version:	ILRIS-3D 2.2.4
System Serial Number:	SN010130
Input total shots:	747360
Input number of scan lines:	864
Input points per scan line:	865
Output total shots:	711072
Output number of scan lines:	864
Output points per scan line:	823
Range:	25.00 m
Spot Spacing:	19 mm
Range Correction:	750.00 cm
Intensity Correction:	0.00
Range Offset:	-9.15 cm
Pulse Mode:	First Pulse
Calibration Frequency:	100 lines
Number of Outliers Removed:	25272

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Name of 3d image file:	FOREST11.I3D
Size of input file:	7978KB
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Time of 3d image file:	15:57:56
System Software Version:	ILRIS-3D 2.2.4
System Serial Number:	SN010130
Input total shots:	747360
Input number of scan lines:	864
Input points per scan line:	865
Output total shots:	711072
Output number of scan lines:	864
Output points per scan line:	823
Range:	19.00 m
Spot Spacing:	14 mm
Range Correction:	750.00 cm
Intensity Correction:	0.00
Range Offset:	-9.15 cm
Pulse Mode:	First Pulse
Calibration Frequency:	100 lines
Number of Outliers Removed:	21791