MEASURING THE URBAN FOREST: COMPARING LIDAR DERIVED TREE HEIGHTS TO FIELD MEASUREMENTS

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Geography

by

Dara O'Beirne

San Francisco, California

December, 2012

CERTIFICATION OF APPROVAL

I certify that I have read *Measuring the Urban Forest: Comparing LiDAR Derived Tree Heights to Field Measurements* by Dara O'Beirne, and that in my opinion this work meets the criteria for approving a thesis submitted in partial fulfillment of the requirements for the degree: Master of Arts in Geography at San Francisco State University.

Jerry Davis
Professor of Geography

Leonhard Blesius
Assistant Professor of Geography

MEASURING THE URBAN FOREST: COMPARING LIDAR DERIVED TREE HEIGHTS TO FIELD MEASUREMENTS

Dara O'Beirne
San Francisco, California
2012

Tree height measurement is a key aspect in ecological studies for the critical assessment of forest biomass, carbon stocks, growth, and site productivity. This research investigates the advantages and limitations of using two different densities of airborne LiDAR data compared to three different field devices to measure tree heights within an urban environment. LiDAR data was highly correlated with field measurements for tree height calculation (R^2=0.96 in the Panhandle and R^2= 0.92 in the Antioch site). Statistical error calculations show that not only is the difference between LiDAR and field measurements relatively low, but that error in vertical angle measurements from traditional field methods is a major contributor to the overall accuracy between LiDAR- and field-derived tree heights. These results suggest benefits of using airborne LiDAR data for measuring tree heights in an urban environment.

I certify that the Abstract above is a correct representation of the content of this Thesis.

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Chair, Thesis Committee Date

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Introduction

Tree height measurement is a key aspect in ecological studies for the critical assessment of forest biomass, carbon stocks, growth, and site productivity. Measuring tree height in the field can be labor intensive, expensive, time consuming, and yield large amounts of random error (National Oceanic and Atmospheric Administration 2008). In some cases, such as closed canopy dense forests, field measurements can be near impossible. Foresters and researchers alike have been looking for a more efficient and accurate way to measure canopy height in order to calculate biomass. Light Detection and Ranging (LiDAR) is a remote sensing tool that has the potential to lower random error and measure tree characteristics at various scales.

The concept of LiDAR remote sensing is based on the physical principles regarding light. A LiDAR system makes its measurement based on the distance between a sensor and its target. The distance is determined by the elapsed time of high frequency light pulses that are emitted from a sensor and then the arrival of the reflection of that pulse (return signal) back to the sensor. Multiplying the time interval by the speed of light gives the round trip distance traveled by each pulse of light, and then dividing that number by two gives the distance between the target and sensor (Lefsky et al. 2002). For the purpose of this study when referring to LiDAR, it is in reference to the use of airborne LiDAR. Generally, airborne LiDAR is collected through the use of a helicopter or small fixed wing airplane. Other methods of collection include ground-based laser systems or satellites. The primary concern of this research is in regards to the collection of airborne LiDAR in order to measure and model tree heights.

LiDAR is a remote sensing technology that is used for various mapping purposes such as digital terrain modeling (DTM), above-ground feature extraction, bird population modeling, ice sheet mapping, flood plain mapping, landslide detection, and land cover classification (Lim et al., 2003b). For the last 20 years LiDAR has been used for the field of forestry and environmental measurements (Hyyppa et al., 2001; Lefsky et al., 1999; Means et al., 1999; Nilsson, 1996). LiDAR technology provides horizontal and vertical data that have high spatial resolutions and vertical accuracies (Ahokas et al., 2003). Attributes of forests, such as canopy height, can be derived directly from the use of LiDAR data. In addition LiDAR can also be used to estimate and model above-ground biomass and canopy volume in a given forest (Lim et al. 2003a; Sexton et al. 2009).

The original intent for the application of LiDAR in the use of measuring forest characteristics can be traced back to the early 1980s when it was used to map forests in Central America (Renslow 2012). Then, in the mid-1980s researchers used cross-sectional photogrammetric methods in order to show that an area of the forest canopy was linearly related to the natural log of timber volume (Lim et al. 2003b). It was then assumed that if LiDAR could provide this same cross-sectional data, the volumetric characteristics of a forest could be derived. Early studies regarding the application of LiDAR for forestry focused on the verification of accuracy through the use of statistical methods that could be employed to measure forest attributes. Although it was relatively early regarding the development of the technology, the methods of testing LiDAR against field-based measurements remain the same today (Hyyppa et al. 2004).

Two factors that can influence the accuracy of LiDAR data for tree height measurement are point density and the altitude at which the data were collected. Point density plays an important role because tree tops can be missed and the height underestimated as a result (Morsdorf et al., 2004; Zimble et al., 2003). Altitude of the airplane or helicopter at the time of collection may influence the accuracy of LiDAR derived data as discussed by Goodwin et al. (2006), because altitude influences point density and laser beam footprint size. A larger footprint size of laser beam will result in a lower post-spacing or point density in the data.

Sources of error can occur in both the conventional field measurements of tree and also LiDAR measurements of tree height. McGaughey et al. (2004) reported that errors in the LiDAR derived tree height measurements can be influenced by low lying vegetation and micro-relief up to 0.5 m; this is an important factor to consider when deriving LiDAR tree heights. Also, the quality of data underneath a tree crown may be impacted by the number of hits that penetrate the vegetation and the impact that a tree stem may have on the LiDAR returns. Yet, Hyyppa et al. (2004) argued that the accuracy of conventional field methods may not be sufficient for detailed evaluation of error in LiDAR tree height measurements.

Common sources of error lie within the actual measurement of tree heights in the field. Many researchers use an indirect method of tree height measurement with a digital range finder to determine the distance and angles to both the base and top of surveyed trees, along with an offset of differentially corrected GPS to determine the exact location of a tree. Table 1 provides a brief synopsis of research into LiDAR tree heights compared to various field methods. As shown in table 1 there is a wide range of field methods incorporated that produce an even wider range of results.

Some studies modify their methodology in order to lower their potential level of error. To calculate accurate tree height measurements in the field, Andersen et al. (2006) used the combination of a digital ranger finder and a total station. The total station was used to determine the horizontal distance to the tree and the vertical angle to the base and top of the tree. The most interesting aspect of this method was that they did this from three different locations surrounding the tree, in order to calculate the most accurate height for the top of the tree. Though this may be very accurate, it is extremely time consuming and probably not feasible over large areas.

The methods used in this study incorporate both field measurements and remotely sensed LiDAR data to determine the physical characteristics of trees, primarily tree height. Research has shown that LiDAR data can be used to supplement conventional field methods, especially when sampling and measuring large forested areas (Lefsky et al. 2002). Lim et al. (2003a) measured maximum LiDAR tree heights and performed a regression analysis against forest measurements collected in the field. The results showed that forest characteristics such as height and biomass were highly correlated. The two primary methods for estimating forest characteristics are regression-based methods and individual tree based methods (Malatamo et al., 2005). The individual tree-based analysis examines an estimation of tree counts, the spatial distribution of trees, and tree heights by locating individual trees in forested areas (Koch et al., 2006; Lin et al. 2011). In contrast, the regression-based analysis is used over a larger forested area in order to statistically analyze layers or levels of canopy to predict forest characteristics. This study implements the individual tree-based method rather than the general regression-based method.

Table 1. A summary of the literature on comparing LiDAR- and Field-derived tree heights

Reference	**Laser Pulse Density (Points/m²)**	**Laser Footprint (m)**	**Field Tree Height Estimation Method**	**Relationship/Difference between Field and LiDAR measurement (m)**	**Location**
Yu et al. (2011)	2.60	0.70	Vertex clinometers	**R^2** =.930 **RMSE** = .450	Southern Finland
Hyyppa et al. (2000)	24.0	0.40	Tacheometer	**Mean** = -.140 **RMSE** = .980	Finland
Persson et al. (2002)	4.70	0.26, 0.52, 1.04, 2.03, 3.68	Suunto hypsometer	**RMSE** (different ft prints) = 0.65, 0.72, 0.64, 0.76	Sweden
McGaughey et al. (2004)	4.00	0.40	Impulse hand-held laser	**Mean ± SD** = 0.29 ± 2.23	Northwestern U.S.
Sexton et al. (2009)	4.00 – 6.00	0.50-1.00	Haga altimeter	**R^2** = 0.87 in Pine and 0 .38 in hardwood **RMSE** = 8.40-14.21 in Pine and 9.54-16.84 in Hardwood	North Carolina, U.S.
Thomas et al. (2006)	4.00 and .035	Not Reported	Laser hypsometer	**R^2** = 0.84 for High Density Pts and 0.90 for Low Density	Ontario, Canada
Wang and Glen (2008)	8.00	0.20	Hand-held Laser Rangefinder	**R^2** = .95 **RMSE** =.7	Idaho, U.S.
Patenaude et al. (2004)	2.80	0.25	Theodolites	**R^2** = 0.76	Cambridge shire, U.K.

Study Objectives

The purpose of this study seeks to address questions with respect to advantages and limitations of using two different densities of airborne LiDAR data compared to three different field devices to measure tree heights within an urban environment. Relatively high density LiDAR data can be expensive to obtain, and therefore it is advantageous to compare the accuracy of LiDAR data density that is lower in comparison to another data set in order to determine if relatively low density data will accurately model tree heights.

Much of the current research available on comparing LiDAR-derived tree heights focuses primarily on the accuracy of LiDAR data compared to field measurements. Much less attention has been placed on the error involved within the field methods. While this study also analyzes the relationship between field and LiDAR-derived tree heights, the main objective of this research is to investigate the relationship between sources of error in the field (i.e. vertical angle and distance to the tree) and the error with LiDAR data this study also analyzes the relationship between field and LiDAR-derived tree heights.

Methods and Data

Study Site

The two study areas in this project are Panhandle Park (the Panhandle) in San Francisco, CA and an area with a similar geographic size in Antioch, CA (Figure 1). The Panhandle is located in the geographic center of San Francisco and is a narrow park extending from Golden Gate Park. It was created by William Hammond Hall in 1870 (Pollock 2012). The Panhandle was chosen as a pilot site initially due to data accessibility and its large variety of trees, both tall and short, and both deciduous and conifer. The second study site in Antioch was chosen primarily because of the accessibility to higher density LiDAR data. Antioch is a city located in eastern Contra Costa County in the greater Bay Area. The purpose of having two study sites is to investigate the relationship between LiDAR density, error and the impact that overall height has on error.

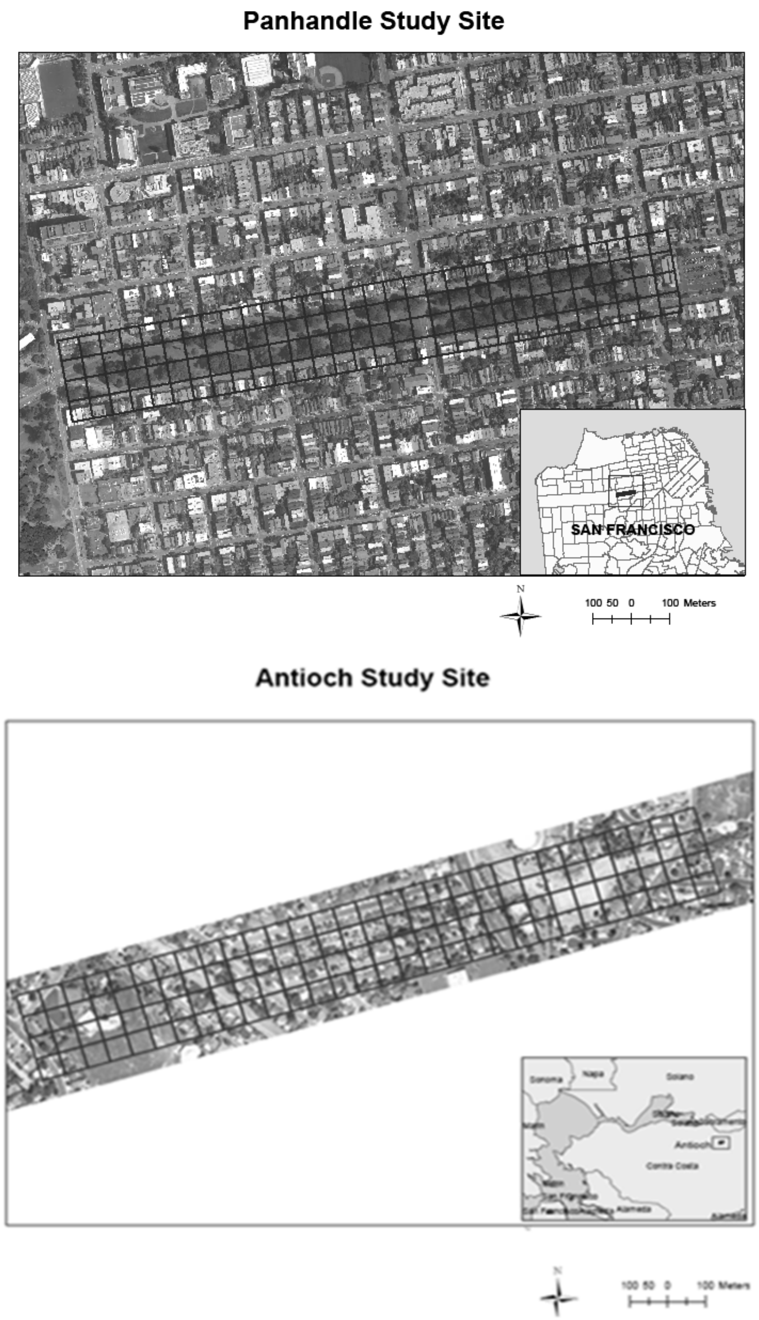


Figure 1. Location of the Panhandle and Antioch study sites

LiDAR Data Acquisitions

The LiDAR data for each site were collected by two different organizations using two very different LiDAR sensors. The LiDAR data for the Panhandle were collected as part of the Golden Gate LiDAR Project through San Francisco State University. The data were obtained by Earth Eye, Inc. on various dates spanning April 23 to July 14, 2010. Earth Eye obtained the data using a Leica ALS60 MPiA (multi-pulse in air) sensor on board a Cessna 207 aircraft. The data acquisition was flown at approximately 2,600 m altitude at a pulse rate of 93 KHZ in order to support a nominal post spacing (resolution) of 2 points per square meter.

The LiDAR data for the Antioch site was collected by Towill, Inc. on August 24, 2010. Towill, Inc. collected the data using an Optech ALTM Orion-200 LiDAR sensor on board a helicopter. The data acquisition was flown at an altitude of 400 meters with a pulse rate of 200 KHz in order to collect a nominal post spacing of 5 points per square-meter (Table 2). The density of the Antioch data is over twice that of the Panhandle data.

Table 2. Parameters of LiDAR Data Acquisition

Site	LiDAR Sensor	Aircraft	Altitude of flight	KHz	Point Density	Acquisition Date
Panhandle	Leica ALS60 MPiA	Fixed wing Cessna	2,600 m	93	2 pts/sq m	04/23-07/14/2010
Antioch	Optech ALTM Orion-200	Rotary Helicopter	400 m	200	5 pts/sq m	08/24/2010

LiDAR Data Classification

The entire LiDAR point cloud for each site was divided into 120 square tiles for easier data management. Each tile containing the LiDAR data is 40 meters by 40 meters in area stored in .LAS file format (Figure 1). The data classification was performed using Terrascan (http://www.terrasolid.fi/), a software program developed by Terrasolid Inc. for viewing and classifying large LiDAR datasets. The classification consisted of ground points, vegetation points and unclassified points (unclassified points are all above ground features that are not classified as vegetation). The ground classification was performed in Terrascan using a predefined algorithm provided in the software. This ground classification algorithm first creates an initial triangulated irregular network (TIN) from local low points that are assumed to be ground hits. Points are then added through an iterative process based on a set of defined geometric parameters until a final ground classification is created. Accuracy of the final digital terrain model (DTM) was assessed using ground control points for each of the study sites. Based on this, the San Francisco data for the Panhandle site had a vertical accuracy of RMSE (z) $\leq$ 0.093 m, and the Antioch data had a vertical accuracy of RMSE (z) $\leq$ 0.046 m.

The vegetation points were then identified through a process of manual classification, along with the tree tops. The tree top for each tree was identified manually in the data and classified to a specific classification called “Tree Tops” (Figure 2).

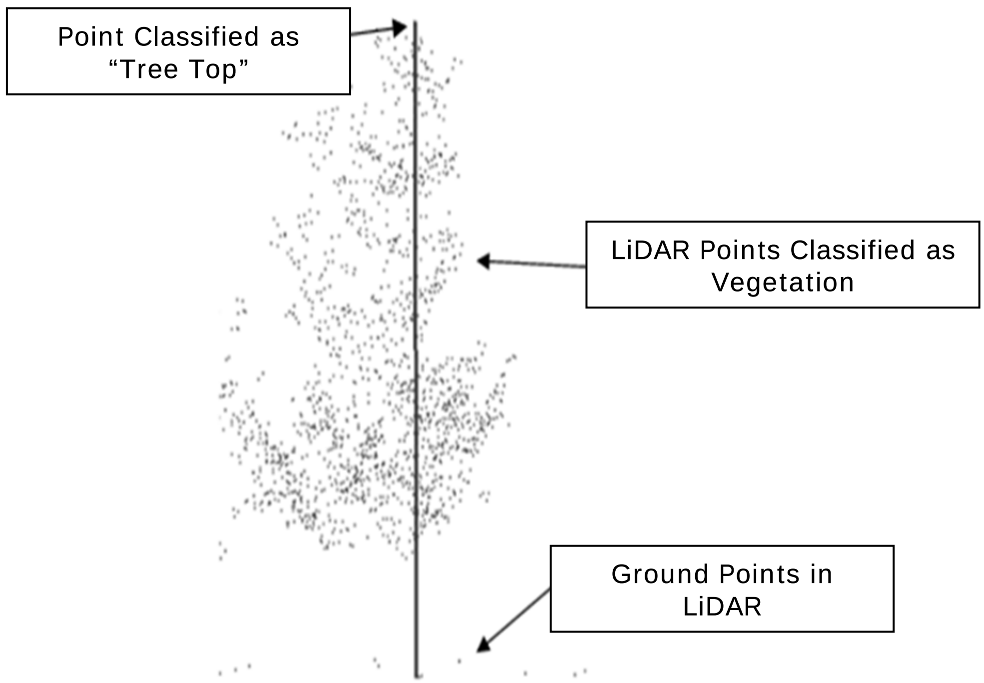


Figure 2. **Cross section of tree from the LiDAR data in Terrascan**

Also using Terrascan, once the tree tops were identified for each tree, a control report was run against the ground in order to determine each tree height. This control report consisted of an x,y,z file for each tree top with a difference in elevation (dz). This dz value is the tree height calculated in the software, which is a vertical measurement from the tree top to the ground (Figure 2).

Field Data Preparation and Sample Design

Researchers have developed many different techniques for measuring individual tree heights in the field (Husch et al. 1982). One of the most direct methods of measuring tree heights up to 25 m involves the use of height poles. This method is subject to error up to 10% due to parallax, which is the displacement in the apparent position of an object along a line of site (Schreuder et al. 1993). However, due to many logistical difficulties in measuring tree heights directly, foresters generally use indirect measurement methods. Most of these methods include the measurements of angles to the tree base (θ) and tree top (ρ), and also the horizontal distance (hd) to the tree stem from the point of measurement (Figure 3) in order to estimate the tree height (H_t) using the following trigonometric formula (Equation 1):

$$H_t = hd(\tan\rho + \tan\theta) \tag{1}$$

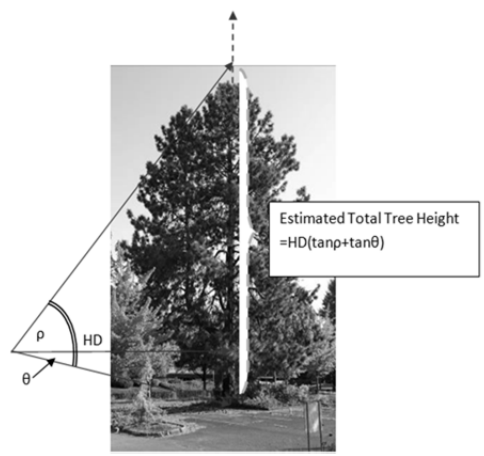


Figure 3. Conventional field method of measuring tree heights in the field using trigonometric principles

Distances to trees are generally measured with an electronic distance measurement device, such as a handheld laser range finder. The angles to the tree base and tree top are measured with either an inclinometer or an electronic angle encoder. Handheld laser range finders are increasingly being used for tree height measurements. A laser range finder is a device that records both distances (using a laser pulse signal) and angular measurements taken from an inclinometer that is integrated into the instrument (Asner et al. 2002). Wing et al. (2004) tested several commercially available digital handheld laser range finders through a series of forestry measurement trials and concluded that most performed within the accuracy ratings claimed by each manufacturer, although significant differences in capabilities did exist among the instruments. However, this method can be extremely difficult and almost impossible in areas of closed stands where it is difficult to see the top of trees.

As part of the sample design each tree top was assigned an individual tree number from the output of the control report. A random number generator was then used in order to determine what trees from the control report list were to be sampled. The selected trees were plotted in ArcGIS over orthophotography in order to aid with field work.

Field Data Collection Laser Rangefinders and GPS

Field data for both the Antioch and San Francisco sites were collected during the fall of 2011. These data were used to analyze and test the differences between field- and LiDAR-derived tree heights. In San Francisco at the Panhandle site n=120 tree heights were measured and in the Antioch site n= 98 tree heights were measured using two different laser rangefinders. Both an MDL Laser Ace 300 laser rangefinder (to be referred to as "Laser 1") and a Laser Technologies Impulse 200 rangefinder (to be referred to as "Laser 2") were used in the field to measure the distance and angles for each tree (Figure 4). According to the manual for the hand held Laser Ace range finder ("Laser 1"), the horizontal accuracy is within 10cm and the vertical degree accuracy is within +/- 0.3° (Measurement Devices Ltd., 2002). On the other hand the Laser Impulse 200 range finder ("Laser 2") reports a horizontal accuracy of 3-5 cm and a vertical accuracy of +/- 0.1° (Table 3) (Laser Technology, Inc., 2011).

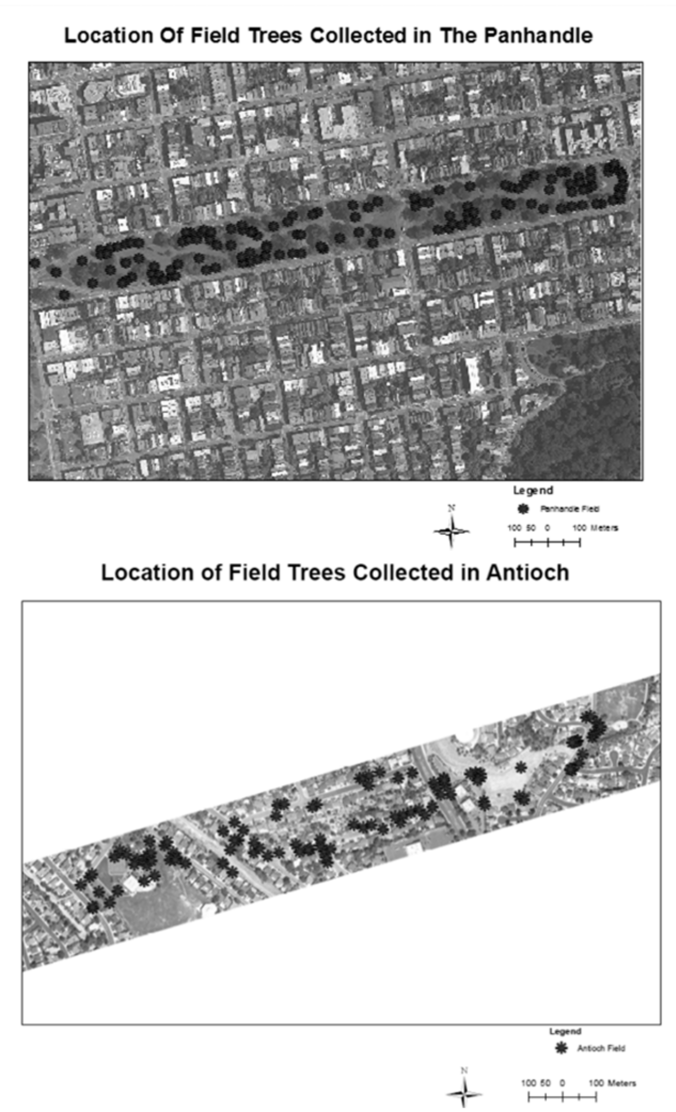


Figure 4. Trees collected in the field for both study sites

In order to determine the location of each tree a Trimble Juno SB handheld GPS receiver was used along with a Suunto KB-14 Aluminum Sighting Compass and the laser rangefinders to determine tree offsets from each recorded location. A series of GPS locations (Figure 5) were recorded and a distance from the laser rangefinder along with an azimuth from the Suunto compass for each tree was used in order to determine the location of each tree.

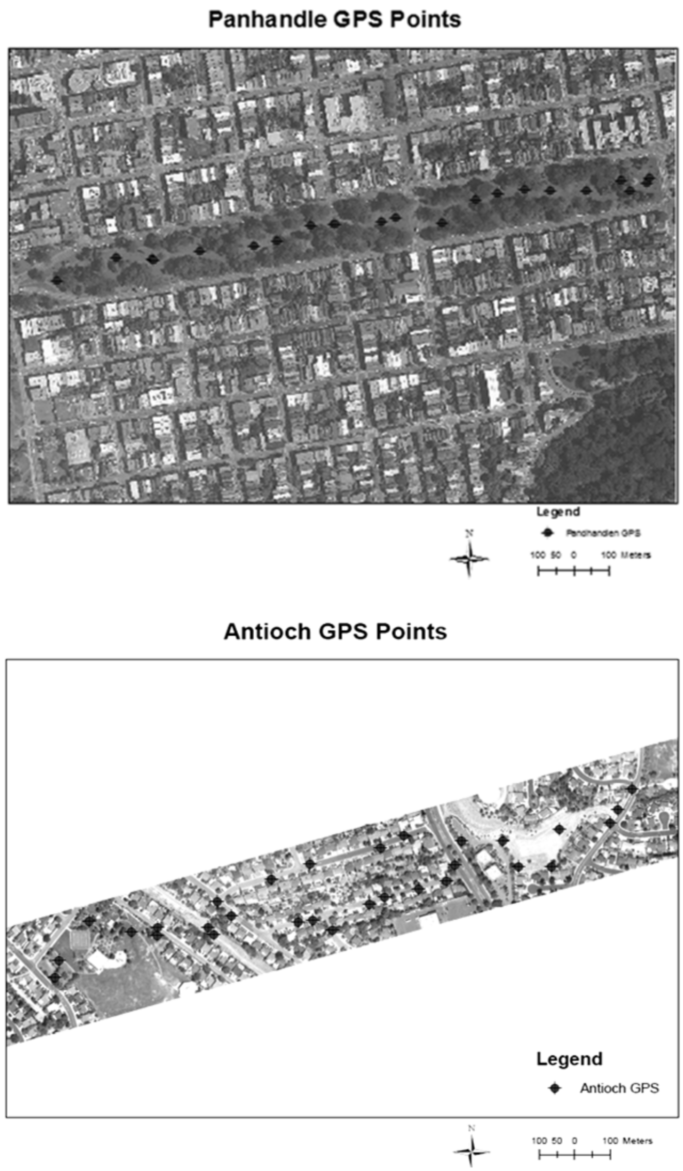


Figure 5. **GPS points collected in the field for both study sites**

Table 3. Accuracy specifications for each instrument used in the field according the manufacturer's manual

INSTRUMENT	HORIZONTAL ACCURACY	VERTICAL ACCURACY	MAX DISTANCE
Laser Technology Impulse 200	3-5 cm	+/- 0.1°	575 m
Laser Ace 300	10 cm	+/- 0.3°	300 m
Topcon GTS-235	0.2 cm	+/- 5" or 0.00138°	3,000 m

Field Data Collection Total Station

In order to test the accuracy of the rangefinders against a more precise and accurate measuring device a Topcon GTS-235 total station was used to measure the height of $n=12$ trees in the San Francisco Panhandle site, in January 2012 (Table 3). The total station was set up in three different locations, and the horizontal distance, vertical angle, and base angle were measured for all visible trees from each location. The method used to measure tree heights with the total station is the same method used for the laser rangefinders (Figure 3). Using this method for the entire site is not feasible because, although it is assumed to be more precise and accurate, it proved to be excessively time consuming and would be inefficient when surveying large wooded areas.

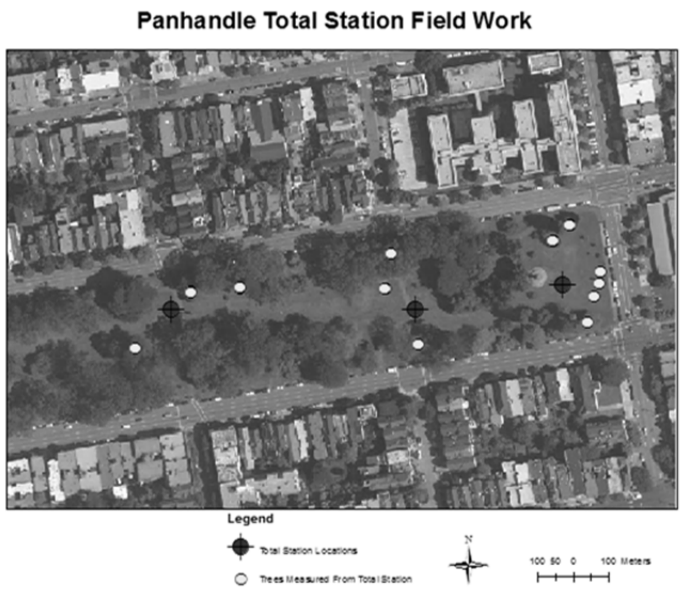


Figure 6. **Twelve trees sampled using the total station**

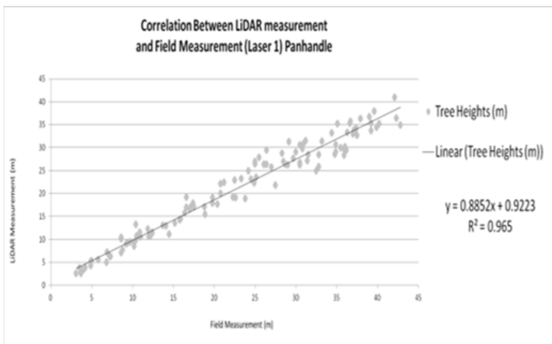
In order to determine the location of each tree using the total station method a Trimble GeoXH 2008 GPS receiver was used (Figure 6). For each tree, two measurements of distance and azimuth were taken on each side of the tree trunk and averaged in order to achieve a more accurate reading.

Results/Analysis

LiDAR Compared to Laser Rangefinder Field Measurements

Individual tree heights measured in the field using two different handheld laser range finders were compared statistically against those same trees measured with airborne LiDAR data (Figure 7). Note that the Panhandle site had a mean tree height of 22.18 m whereas the Antioch site had a mean tree height of 9.47 m. This is important to consider due the relevance that tree height may have on error and accuracy within this study. The R^2 value for both sites between the handheld laser rangefinders and the LiDAR varied from 0.92 (Antioch) to 0.96 (Panhandle) (Table 3). In most of the published literature comparing LiDAR tree heights to field measurements the R^2 value tends to range from 0.76 to 0.95 (Table 1). In comparison to the other research, the R^2 values in this study are on the higher end of most of the published work.

a)



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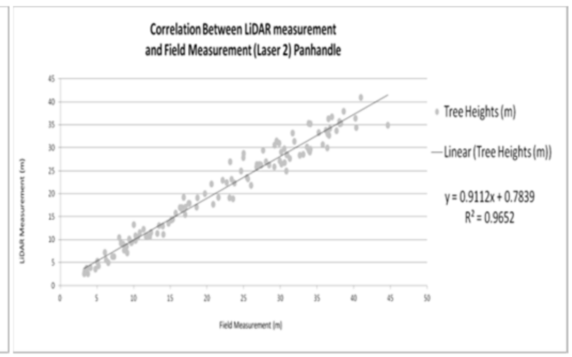

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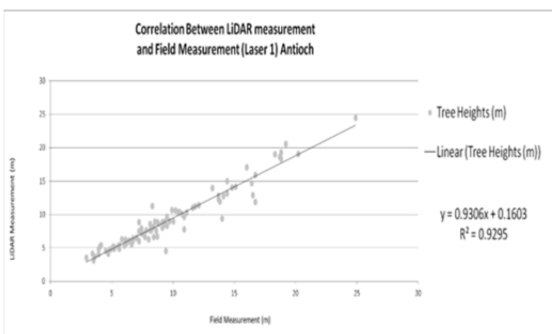

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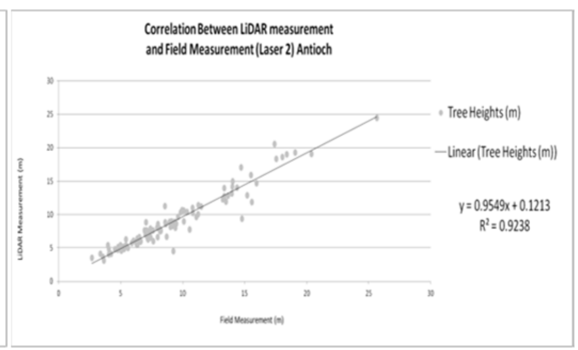


Figure 7. Correlation analysis between a) Laser 1 and Panhandle LiDAR data b) Laser 2 and Panhandle LiDAR Data c) Laser 1 and Antioch LiDAR data d) Laser 2 and Antioch LiDAR data

An independent sample two-tailed t-test was conducted in order to determine if the null hypothesis, that the two means between the LiDAR- and field-derived methods are the same, can be rejected or accepted ($p<0.05$). The results of the t-test show that the means are similar and therefore the null hypothesis can be accepted (Table 4). These results are in accordance with other studies (Brandtberg. 2007 and Popescu et al. 2003) that have found no significant difference between field- and LiDAR-derived tree heights.

Table 4. Summary statistics for both the Panhandle and Antioch sites

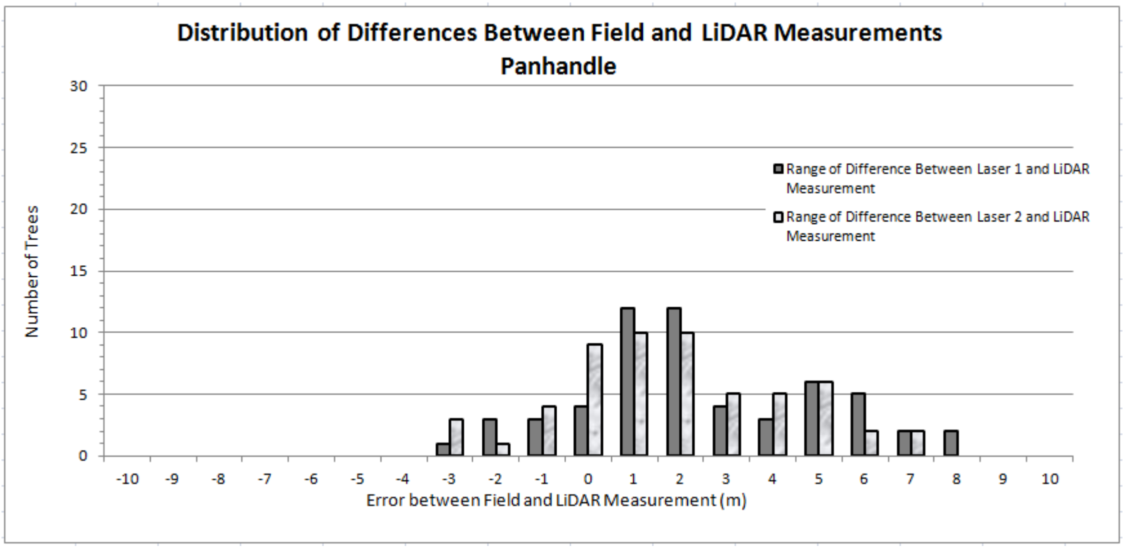
Statistical Analysis	Panhandle Laser 1	Panhandle Laser 2	Antioch Laser 1	Antioch Laser 2
R^2 compared to LiDAR	.96	.96	.92	.92
Std Deviation	11.69	11.35	4.47	4.34
Critical *t*-value *p<0.05*	.260	.420	.430	.630
Mean field height (μ) m	22.28	21.80	9.47	9.27
Mean LiDAR height (μ) m	20.65		8.98	

The results from the correlation analysis confirm previous studies that in general the LiDAR data can measure trees accurately when compared to the field measurements (Drake et al. 2003; Goodwin et al. 2006; Sexton et al. 2009). Although the magnitude of error between the LiDAR and field-derived tree height measurements slightly vary within each site and among the various instruments, the overall accuracy is high.

The distribution of error for both sites using Laser 1 and Laser 2 is normally distributed with the majority of measurements having an error within 2 meters. The range of error is wider in the Panhandle site than it is in the Antioch site (Figure 8). This is possibly due to the fact that the Antioch site had an overall shorter tree height and a lower RMSE.

A positively biased distribution of error shows that the errors tended to be on the higher end of the distribution, representing an overestimation of tree heights from the field methods or under estimation from LiDAR. There are factors from both LiDAR and field measurements that can contribute to an inconsistency in tree heights. If a measurement in the field is taken too close to a tree it may be difficult to identify the top of the tree and result in a higher recorded height (Figure 9). In regards to LiDAR data, laser pulses, especially small-footprint LiDAR, have the potential to completely miss the top of a tree and therefore record a lower height (Renslow 2012). This is difficult to account for and is near impossible to correct in the LiDAR data.

a)



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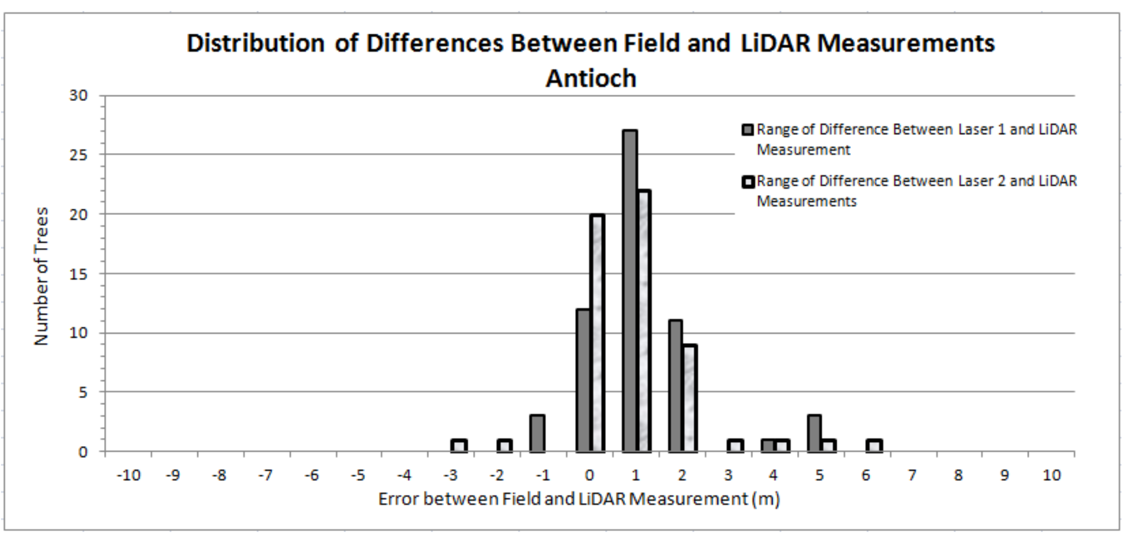

Figure 8. A distribution of error from LiDAR and field measurement analysis between a) Laser 1 & 2 and Panhandle LiDAR data b) Laser 1 & 2 and Antioch LiDAR Data

In order to determine if tree height influences error, a linear regression analysis was performed between tree height and error. Based on a 95% confidence level (*$p<0.05$)* using both lasers for the Panhandle and Antioch sites, the regression analysis showed a relationship between height and error. The relationship between height and error (figure 10) was weaker in the Antioch site (Laser 1 had R^2= 30.6 and Laser 2 had R^2=33.6, $p<0.05$) compared to the Panhandle site where the significance and linear regression fit was higher (Laser 1 had R^2= 61.7 and Laser 2 had R^2 = 56.4, $p<0.05$). The stronger regression fit for the Panhandle site may be due to the fact that the trees are taller and the range of error is higher in this situation. These regression results show that tree height is a limiting factor when measuring in the field.

Another analysis was conducted to investigate the relationship that height has on error by comparing the vertical angle in the field to the error between field and LiDAR measurements. The R^2 values ranged considerably, from as low as .03 in Antioch up to .31 in the Panhandle and as large as .48 for the total station in the Panhandle site. The strong relation between error and vertical angle in the Panhandle site supports the argument that vertical angle has a large impact on error from field measurements.

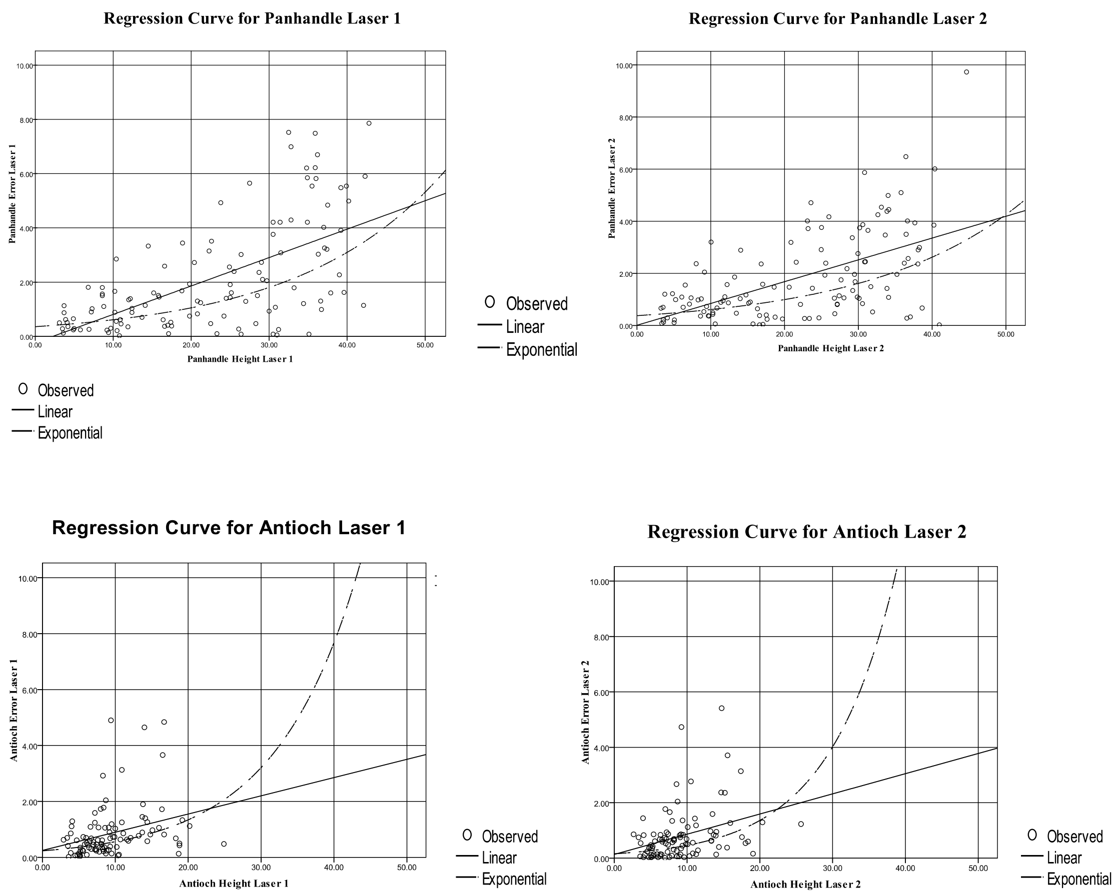

Figure 9. **A regression curve for the relationship between tree height and error**

The relationship between tree height and error appears to be relevant in this study; the taller the tree, the higher the error (Figure 9). This relationship can be explained by error from the field methods. In the LiDAR data, error should not be impacted by height, because the error would be systematic regardless of tree height. Trees that have a large crown and are tall can make it difficult to identify the true top from a ground perspective in the field (Figure 10). As a result a higher angle will be measured and a false overestimation may occur.

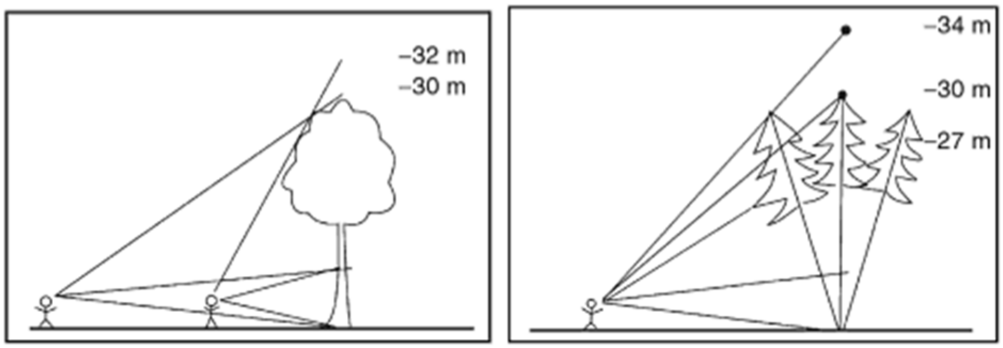

Figure 10. Sources of error in height measurements (from Kohl et al. 2006)

LiDAR compared to Total Station Field Measurements

As stated earlier *n*=12 trees were measured using a Topcon GTS-235 total station in the Panhandle in order to determine the accuracy of the two hand-held laser range finders. The results and differences between the LiDAR and each field method for the 12 trees measured are in Table 5. The field measurements overestimate the height compared to the LiDAR data for the 12 trees sampled using the total station (Figure 8). The columns with the headings L1-LiDAR and L2-LiDAR show the overestimation or underestimation of each measurement. A positive number reflects an overestimation of tree height in the Field. These differences will be explored in depth later, but it is useful to note the differences between handheld laser rangefinders and the total station against the LiDAR-derived tree heights.

Table 5. **Tree height measurements using four devices and their differences for 12 selected trees**

Tree ID	L1 (m)	L2 (m)	Total Station (m)	LiDAR (m)	L1-L2 (m)	L1-Total (m)	L2-Total (m)	L1-LiDAR (m)	L2-LiDAR (m)	Total-LiDAR (m)
119	39.90	40.37	43.31	34.36	-0.47	-3.41	-2.94	5.54	6.01	8.95
122	6.80	6.54	6.33	4.99	0.26	0.46	0.20	1.81	1.55	1.34
134	15.80	15.15	16.28	14.29	0.65	-0.48	-1.13	1.51	0.86	1.99
137	12.40	12.39	13.58	11.52	0.01	-1.18	-1.19	0.88	0.87	2.06
219	34.80	33.13	34.31	28.59	1.67	0.48	-1.18	6.21	4.54	5.72
228	30.50	28.47	30.64	26.29	2.03	-0.14	-2.17	4.21	2.18	4.35
242	16.40	15.73	17.24	15.79	0.67	-0.84	-1.51	0.61	-0.06	1.45
254	3.10	3.26	3.85	2.60	-0.16	-0.75	-0.59	0.50	0.66	1.25
255	3.50	3.57	4.13	3.78	-0.07	-0.63	-0.56	-0.28	-0.21	0.35
256	3.70	3.53	3.66	2.83	0.17	0.03	-0.13	0.87	0.7	0.83
257	4.20	4.13	4.32	3.84	0.07	-0.12	-0.19	0.36	0.29	0.48
276	22.50	22.16	22.99	22.97	0.34	-0.49	-0.83	-0.47	-0.81	0.02

The statistical error measurements, Root Mean Squared Error (RMSE), Absolute Mean Error (ABSE), Mean Error (ME), and Maximum Error (MAXE) were used to compare the LiDAR derived tree heights and the field measurements (Table 6).

$$RMSE_z = \sqrt{\frac{\sum_{i=1}^{n}(Z_{F,i} - Z_{L,i})^2}{n}} \tag{2}$$

$$ABSE_z = \frac{\sum_{i=1}^{n}|Z_{F,i} - Z_{L,i}|}{n} \tag{3}$$

$$ME_z = \frac{\sum_{i=1}^{n}(Z_{F,i} - Z_{L,i})}{n} \tag{4}$$

$$MAXE_z = MAX_{i=1}^{n}|Z_{F,i} - Z_{L,i}| \tag{5}$$

where Z_L is the height of LiDAR measured tree height and Z_F is the height of the field measured tree height.

The ABSE and ME are measures of deviation of the LiDAR heights from the field measurements. The mean error is a measure of systematic bias, it describes the overall bias of the LiDAR data to overestimate or underestimate heights compared to field measurements. The RMSE is a measure of the average magnitude of error, but does not indicate the direction of errors, whether it is positive or negative, that is what ME does. The MAXE describes the largest amount of deviation between LiDAR- and field-derived tree heights.

Table 6. Statistical error measurements

ERROR	Panhandle Laser 1	Panhandle Laser 2	Antioch Laser 1	Antioch Laser 2
Root Mean Squared Error	2.88	2.48	1.28	1.23
Absolute Error	2.10	1.83	0.87	0.81
Mean Error	1.63	1.15	0.49	0.29
Maximum Error	7.86	9.73	4.90	5.41

The mean error for the Panhandle site is over twice the mean error for the Antioch site (table 6). In order to see if tree height in the Panhandle site influences the error from field measurements compared to the Antioch site, calculating the mean error from trees within a certain height range may provide evidence. The mean height for trees in the Antioch site from field measurements was between 9.3 and 9.5 m. Therefore, calculating the mean error from trees in the panhandle site below 10 m provides evidence that height influences error. The mean error from the field measurements of trees below 10 m in Antioch is 0.48 m for Laser 1 and 0.39 m for Laser 2. In the Panhandle site mean error for trees below 10 m was 0.58 m for Laser 1 and 0.46 m for Laser 2. Thus the difference in mean error between the two sites is smaller for trees <10m than for all trees. This leads to the conclusion that tree height plays a large role in the mean error from the Panhandle site.

Differential of height error

When measuring trees using the tangent based method, as is done in this study, there are multiple sources of error that are both systematic and random. The tangent based method is applied with the assumption that the top of the tree is directly over the base, which is not often the case. If the tree is either leaning or the top is not directly over the base of the tree, crown offset point errors can occur. Assuming the tree is perfectly vertical and the top is directly over the base, slight errors can still occur from the various measuring devices. A useful approximation of error can be calculated by using partial derivatives (Equation 6). The following equation determines the potential magnitude of error by calculating the height error that results from a given error in vertical angle or distance error using the tangent based method (Larson and Edwards 2010; Leverett 2011.):

$$
\begin{aligned}
h &= D\tan(a) \\
dh &= D\frac{\partial \tan(a)}{\partial a}da + \tan(a)\frac{\partial D}{\partial D}dD \\
dh &= D\sec^2(a)da + \tan(a)dD \\
dh &= \frac{D}{\cos^2(a)}da + \tan(a)dD
\end{aligned} \tag{6}
$$

where (*D*) is the horizontal distance, (*a*) is the vertical angle, (*da*) is the potential error in vertical angle, and (*dD*) is the potential error in horizontal distance.

Table 7. Differential height errors from both angle and distance for the 12 trees measured using the total station

Tree ID	D (m)	a (°)	tan(a)	$\cos^2(a)$	dh (m) da (°)=1 dD (m)=1	dh (m) da (°)=1 dD (m)=0	dh (m) da (°)=0 dD (m)=1
119	39.74	46.82	1.066	0.468	2.55	1.48	1.06
122	24.87	11.99	0.212	0.957	0.67	0.45	0.21
134	29.77	26.69	0.503	0.798	1.15	0.65	0.50
137	38.94	17.26	0.311	0.912	1.06	0.75	0.31
219	34.72	44.51	0.983	0.509	2.17	1.19	0.98
228	54.36	29.13	0.557	0.763	1.80	1.24	0.55
242	22.25	34.89	0.697	0.673	1.27	0.58	0.69
254	19.56	6.99	0.123	0.985	0.47	0.35	0.12
255	25.95	6.63	0.116	0.987	0.58	0.46	0.11
256	23.5	5.77	0.101	0.990	0.52	0.41	0.10
257	21.57	8.39	0.147	0.979	0.53	0.38	0.14
276	29.38	37.5	0.767	0.629	1.58	0.81	0.76

Table 7 shows the potential magnitude of height error (*dh*) assuming 1 degree for potential error in vertical angle and 1 m for potential error in horizontal for the 12 trees sampled using the total station. Although an observer may not be aware of the angle and distance measurements, it is interesting to explore the extent of height error from small measurement errors. The errors in measurement can be associated with both user error and/or equipment error. A significant source of user error is in the identification of the true top of the tree. In tall deciduous trees with large crowns it can be difficult to identify correctly the exact location of the tree top and therefore result in either an over or underestimation in height (Avery and Burkhart 1983). Considering that a large portion of the trees in the Panhandle were tall deciduous trees with large crowns this factor could have an impact on the error results from the Panhandle. Another important source of error to consider from the use of a total station is the difficult field of view. The field of view from a total station is much smaller than a digital range finder which can make the identification of a tree top more difficult. This source of error can potentially exaggerate the error in the vertical angle measurement (Da) and therefore create larger height error measurements. For instance tree 119 in table 7 has the highest potential error because it also has the largest vertical angle measurement creating more potential for error.

Table 7 also shows the differential error that may occur from error in only the vertical angle measurement or distance measurement. Assuming that the distance (D) measured to a tree trunk has no error this table shows the height error that can result from a slight vertical error (1°) in the measurement to the tree top. The range of error in this example is ranging from 0.38 to 1.48 (m). Similarly, assuming the vertical angle (a) measured to the top of a tree has no error table 7 also shows the height error that can result from a slight horizontal distance (D) error in the measurement to the tree trunk.

To determine the impact vertical and distance error have on the measurements in this study, equation (6) was used to compare the error between the field and LiDAR measurements to see which of the two, angle or distance error had a larger impact. A correlation between potential error based on the equation and actual error from LiDAR and field measurements show a strong relationship. The R^2 for *dh* compared to the LiDAR and total station measurements when *da*=0 and *Dd*=1 was 0.54, but the R^2 for *dh* compared to the LiDAR and total station measurements when *da*=1 and *Dd*=0 was much higher, 0.79. For the total station measurements this provides evidence that the vertical angle has a larger impact on overall error than distance. This same analysis was run for the both sites using the two rangefinders. The R^2 values for distance ranged from 0.03 to 0.28, and the R^2 values for angle ranged from 0.04 to 0.31, in both cases with a much stronger relationship in the Panhandle site than the Antioch site. The site with overall taller trees had a stronger correlation between error and vertical angle measurement than the site with shorter overall trees.

Discussion

This study has shown that the relationship between both the LiDAR- and field-derived measurements in both sites is considered to be strong (R^2= 0.92 - 0.96). Although the magnitude of error is different for each site the results show that both the low density and the high density LiDAR can accurately measure tree heights compared to field measurements (Figure 7). Despite the strong relationship between the field measurements and LiDAR measurements, the error measurements differ substantially. For example, the absolute error in the Panhandle site (1.634 m) using laser 1 is more than three times larger than the Antioch site (0.497 m).

Although the R^2 for the Panhandle was higher (0.96) than the Antioch site (0.92), the statistical error measurements for the high density LiDAR data were considerably lower than the same measurements for the low density LiDAR (Table 6). Therefore, it can be concluded that the high density LiDAR (5 points/m^2) is more accurate than the low density LiDAR (2 points/m^2) for measuring individual tree heights. However, the site with the high density LiDAR (Antioch) also had an average tree height approximately half that of the low density site (Panhandle), and when comparing similar tree heights between sites the level of error was comparable between both sites. This is attributed to the fact that tree height can influence the level of accuracy as well, as there are steeper angles.

Regardless of tree heights influencing the accuracy of field measurements, LiDAR too can influence the level of error. Assuming that the vertical and horizontal accuracies are within acceptable ranges, the laser beam can miss the tree top causing an underestimation of tree height (Figure 11). Zimble et al. (2003) found that this occurred when small footprint laser beams were used or with large post spacing (low density LiDAR data). Therefore, it is possible that tree tops that were identified in the LiDAR were actually from LiDAR hits within the crown and not the true top of the tree. Therefore this factor is a possible explanation for why the field measurements overestimated LiDAR tree heights in the low density LiDAR more than they did in the high density LiDAR.

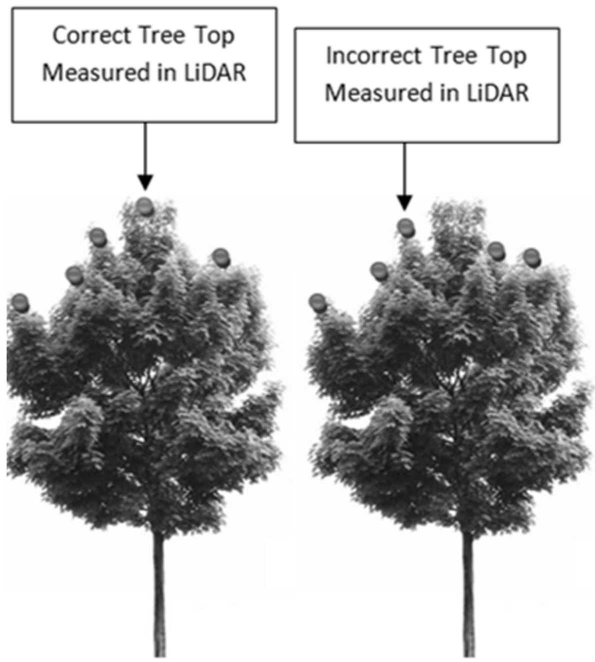

Figure 11. Example of how LiDAR points can miss the top of tree and result in an incorrect tree height measurement in the LiDAR

Another factor that can lead to error in measurement is the identification of tree tops in the field. The tops of many tall deciduous trees are not distinctively pointed, resulting in difficulty to identify the tree apex from the ground (Tickle et al. 2006). It is then likely that in some cases this is a reason for an overestimation of tree height in field compared to the LiDAR. Similar to this study Gaveau and Hill (2003), Maltamo et al. (2004), and Ronnholm et al. (2004) all found that their field measurements consistently overestimated tree heights compared to the LiDAR, for both conifer and deciduous trees. For tall trees, slight differences in the angle to the top of tree can result in larger errors of height measurement (Table 7). With only 1 degree in vertical error and no error in horizontal distance the height error ranges from 0.4-1.5 m for the trees measured using the total station. In order to investigate this, a differential height error measurement was used.

The differential height error equation (Equation 6) investigates the relationship that errors from both the vertical angle and distance have on tree height measurements using the tangent method. Although it is well known that the angular and horizontal precision is extremely high for a total station (Anderson et al. 2006), errors in this situation can occur randomly as a result of human mistakes. Determining the location of the exact tree top is extremely subjective in the field. One person's interpretation of a tree top can be different from another's in the field. Even slight misidentification can change the vertical angle and therefore, result in a height error. Determining the magnitude of error is important. As seen in Table 6, a simple 1 meter distance error combined with a 1 vertical degree error can lead to a 2.54 meter difference in height.

Conclusion

The application of LiDAR for measuring tree heights can prove to be within certain accuracy standards comparable to methods used in the field. In numerous previous studies, along with this one, tree height measurements from LiDAR have been shown to be highly correlated with tree heights measured in the field using conventional field methods (Yu et al. 2011; Sexton et al. 2009; Thomas et al. 2006; Wang and Glen 2008). However, because all conventional field methods also introduce errors in the measurement of tree heights, it is difficult to obtain a definitive statement of accuracy for LiDAR-derived tree height measurements. In this study, two different densities of LiDAR were compared to field measurements and the level of error was lower for the higher density data; however, the site with higher density data also had shorter trees, which could also account for a lower level or error.

This study showed that the random error and extensive labor to measure trees in the field creates much greater error as compared to the results from the LiDAR. The major factor relating to error from field methods are related to tree height; therefore, it may be more advantageous to use LiDAR data to measure tree heights in an urban environment. The error that occurs during field measurements is not only difficult to quantify, but is near impossible to correct for. Because it is difficult to quantify the absolute error from the field heights a definitive statement for the accuracy of LiDAR compared to field measurements is difficult.

The differential height error equation was used to show how dependent tree height accuracy is on the vertical angle and distance in the field. Future studies should collect multiple measurements of each tree using the same instrument, and then the variations in angles and distances can be examined to investigate the magnitude of error further. If multiple measurements for the vertical angle to the tree top were to be collected we could measure the potential magnitude of error based on the range of angles. This would provide a more precise measurement for both tree heights and the resulting error. Future research regarding the accuracy of LiDAR tree heights compared to field measurements should incorporate a more accurate field method. For example, as discussed by Bragg (2008), the sine method is a tree height measurement method that takes in to consideration the error resulting from leaning trees or offsetting crowns.

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APPENDIX A: FIELD DATA

PANHANDLE FIELD DATA:

GPS PT	TREE ID #	Height (m) Laser1	Height (m) Laser2	Difference b/w Laser 1&2	LiDAR Tree Height (M)
1	134	15.8	15.15	0.65	14.29
1	135	26.4	27.14	-0.74	26.32
1	137	12.4	12.39	0.01	11.52
1	136	15.2	14.77	0.43	13.6
1	138	4.9	5.24	-0.34	4.25
1	139	3.7	3.77	-0.07	2.57
1	253	3.9	3.36	0.54	3.28
1	276	22.5	22.16	0.34	22.97
1	275	27	26.76	0.24	25.71
2	273	12	12.22	-0.22	10.65
2	272	17.5	17.08	0.42	17.12
2	248	27.5	26.02	1.48	21.85
2	247	22.3	21.58	0.72	19.15
3	131	19.8	17.63	2.17	17.87
3	129	9.7	9.76	-0.06	9.4
3	125	26.4	27.67	-1.27	29.42
3	127	23.8	23.58	0.22	18.87
3	128	16.6	16.83	-0.23	19.19
4	126	20.4	20.87	-0.47	17.68
4	124	26.1	26.82	-0.72	26.37
4	120	37.5	36.67	0.83	32.66
4	119	39.9	40.37	-0.47	34.36
4	122	6.8	6.54	0.26	4.99
4	239	7.3	7.34	-0.04	6.28
4	240	20.8	20.63	0.17	22.1
4	241	32.8	30.96	1.84	28.51
4	270	17.1	16.62	0.48	17
4	242	16.4	15.73	0.67	15.79
5	116	25	30.18	-5.18	26.43
5	110	10.4	10.05	0.35	13.25
5	112	10.4	10.28	0.12	9.85
5	114	25	23.19	1.81	26.91
5	234	19.8	18.73	1.07	19.05
6	228	30.5	28.47	2.03	26.29
6	235	32.8	29.18	3.62	25.81
7	103	32.5	30.85	1.65	24.98
7	219	34.8	33.13	1.67	28.59
7	218	10.8	10.29	0.51	10.78
7	220	42.3	40.25	2.05	36.4
7	224	34.9	34.04	0.86	29.05
7	264	34.9	35.79	-0.89	30.69
8	100	9.2	8.61	0.59	8.97
8	214	36.6	33.88	2.72	35.3
8	263	37.1	36.23	0.87	33.84
8	265	29.15	29.57	-0.42	31.25
9	102	30.8	30.57	0.23	29.73
9	97	11.9	11.36	0.54	12.25
9	99	28.5	28.06	0.44	27
9	215	28.3	25.01	3.29	28.77

10	92	37	36.48	0.52	32.98
10	210	28.7	27.14	1.56	26.34
10	208	35.9	32.66	3.24	28.41
11	202	31.5	30.86	0.64	28.42
12	197	29	27.41	1.59	26.27
12	198	24.9	23.77	1.13	22.34
12	84	25.15	25.47	-0.32	23.54
12	86	35.5	36.44	-0.94	29.96
13	82	11	10.6	0.4	10.54
13	81	33.2	31.93	1.27	31.41
13	80	13.7	13.47	0.23	13
13	195	37.4	36.76	0.64	34.19
14	78	39	37.06	1.94	36.73
14	189	36.7	38.07	-1.37	35.71
14	190	39.2	38.28	0.92	35.29
14	191	14.1	13.99	0.11	12.96
14	187	14.5	14.06	0.44	11.17
14	73	8.6	9.43	-0.83	10.16
14	74	42.8	44.67	-1.87	34.94
15	71	40.2	38.11	2.09	35.21
15	76	10.2	9.68	0.52	9.31
15	77	15.9	15.35	0.55	14.45
15	188	18.9	17.04	1.86	15.46
15	185	20.8	19.72	1.08	19.97
15	186	37.9	36.58	1.32	36.3
15	184	29.7	31.3	-1.6	27.65
15	178	30.5	30.61	-0.11	26.74
16	2	8.6	9.15	-0.55	7.1
16	28	5	5.08	-0.08	5.29
16	142	30	30.11	-0.11	29.07
16	145	24.5	23.37	1.13	23.1
17	6	17	16.61	0.39	16.59
17	34	18.8	18.59	0.21	17.12
17	5	8.8	8.72	0.08	7.7
17	33	10.2	9.07	1.13	8.54
17	11	4.9	5.03	-0.13	5.14
17	9	6.9	6.07	0.83	7.16
17	8	5.8	6.26	-0.46	5.56
17	40	31	29.86	1.14	30.95
17	39	7.2	7.12	0.08	6.3
17	37	22.6	23.1	-0.5	19.09
17	151	42.1	40.98	1.12	40.96
17	155	9.4	8.28	1.12	9.26
17	154	35.1	34.1	1	35.18
17	148	34.4	31.7	2.7	33.19
18	254	3.1	3.26	-0.16	2.6
18	255	3.5	3.57	-0.07	3.78
18	256	3.7	3.53	0.17	2.83
18	257	4.2	4.13	0.07	3.84
21	160	36.2	33.88	2.32	29.5
21	161	25.5	24.98	0.52	27.89
21	158	39.2	37.66	1.54	33.72
21	157	8.6	8.03	0.57	10.4
21	259	31.4	29.95	1.45	27.19
21	164	3.6	3.61	-0.01	3.48
21	163	4.1	4.81	-0.71	3.59
21	166	12.4	13.23	-0.83	11.37
21	167	12.2	11.91	0.29	10.81

20	52	35.9	34.13	1.77	29.68
20	49	36.3	35.23	1.07	33.27
20	45	31.2	29.49	1.71	31.45
20	14	16.6	16.33	0.27	16.97
20	15	10.5	11.66	-1.16	10.71
20	169	36	33.65	2.35	30.18
20	170	39.6	38.65	0.95	37.98
20	172	23.3	25.59	-2.29	23.2
20	61	17.4	17.52	-0.12	17.92
20	18	21.2	22.71	-1.51	22.44
20	57	10.9	10.85	0.05	11.52
20	60	24.2	24.66	-0.46	24.95
20	55	30.5	29.24	1.26	30.58

ANTIOCH FIELD DATA:

GPS PT	TREE ID #	Height (m) Laser1	Height (m) Laser2	Difference b/w Laser 1&2	LiDAR Tree Height (M)
1	532	19.2	17.39	1.81	20.53
1	531	18.8	19.07	-0.27	19.23
2	265	16.5	15.2	1.3	12.84
2	2	14.4	13.95	0.45	13.14
2	533	10.2	10.07	0.13	10.57
2	536	9.1	9.39	-0.29	8.03
2	538	6.7	6.33	0.37	6.4
3	249	9.4	9.23	0.17	4.5
3	252	5.2	5.58	-0.38	4.97
3	255	5.2	4.78	0.42	5.15
3	325	12.1	11.26	0.84	11.4
3	322	13.7	13.65	0.05	12.81
3	327	18.7	18.03	0.67	18.57
3	328	24.9	25.65	-0.75	24.42
4	541	9.5	9.61	-0.11	9.64
4	543	9.1	9.18	-0.08	8.83
4	275	14	14.76	-0.76	9.35
4	440	16	14.69	1.31	17.06
4	439	16.4	15.95	0.45	14.68
4	442	8.4	9	-0.6	8.18
4	444	6.5	6.58	-0.08	5.92
4	276	10.7	11.24	-0.54	10.06
5	520	6	5.44	0.56	5.3
5	283	7.4	7.33	0.07	7.11
5	286	8.5	8.92	-0.42	8.86
6	279	10.9	11.08	-0.18	9.65
7	562	14.8	14.38	0.42	13.98
8	316	13.2	13.35	-0.15	13.97
9	35	9.3	9.36	-0.06	8.91
9	36	7.2	7.62	-0.42	5.96
9	38	6.1	6.33	-0.23	6.19
9	39	13.8	13.49	0.31	11.9
10	33	5.8	5.41	0.39	6.27
10	600	8.2	8.22	-0.02	7.59
10	28	5.1	5.1	0	5.07
10	27	3.9	4.52	-0.62	4.76
11	591	10	9.1	0.9	8.97
11	24	7	7.14	-0.14	6.45
11	587	7.7	6.5	1.2	6.63

12	582	7.4	6.91	0.49	7.64
12	577	4.8	4.75	0.05	4.72
12	332	4	5.07	-1.07	5.11
12	321	20.2	20.37	-0.17	19.08
13	725	9.5	9.06	0.44	8.31
13	318	18.3	18.38	-0.08	18.98
13	5	18.8	17.54	1.26	18.3
13	4	16.7	15.57	1.13	11.86
14	145	8.7	8.58	0.12	8.84
14	146	9.7	10.09	-0.39	8.97
14	151	3.9	4.03	-0.13	4.06
15	161	6.1	6.26	-0.16	5.58
15	160	8.6	8.23	0.37	7.54
16	164	10.4	9.83	0.57	10.33
16	165	11.1	10.8	0.3	10.24
16	168	8.3	7.92	0.38	8.01
16	167	5.2	5.21	-0.01	4.85
16	172	10.5	10.33	0.17	10.4
17	174	14.1	13.33	0.77	12.7
18	456	11.6	10.79	0.81	10.96
18	458	8	7.2	0.8	6.27
18	678	9.9	9.94	-0.04	10.63
18	679	16.7	15.5	1.2	15.88
19	628	5.6	4.04	1.56	4.87
19	632	6.7	6.61	0.09	6.02
19	639	7.2	8.16	-0.96	7.48
20	77	3.4	3.35	0.05	4.1
20	648	7.4	7.39	0.01	7.87
20	650	8.1	8	0.1	8.57
20	656	7.6	6.98	0.62	6.98
20	671	9.3	9.46	-0.16	8.62
21	677	10.9	10.54	0.36	7.77
21	97	8.7	8.7	0	6.66
22	64	11.8	11.49	0.31	11.21
23	460	4.1	3.95	0.15	5.39
23	461	5.1	5.09	0.01	5.2
24	472	5.6	4.97	0.63	5.37
24	473	6.4	6.02	0.38	6.05
24	479	4.7	4.21	0.49	4.09
24	478	5	5.28	-0.28	4.86
24	471	2.9	2.67	0.23	3.53
24	470	3.5	3.63	-0.13	3.09
25	491	3.6	3.56	0.04	3.62
26	117	13.7	13.22	0.48	12.25
26	116	7.2	7.02	0.18	8.79
27	120	14.4	14.03	0.37	14.98
27	121	9.2	9.16	0.04	8.3
28	715	8.3	8.55	-0.25	11.22
28	714	6.2	5.89	0.31	5.75
29	514	6.6	6.35	0.25	5.51
29	513	7	7.41	-0.41	6.54
29	719	4.5	5.04	-0.54	4.57
30	256	8.4	7.96	0.44	6.62
30	257	5.5	5.33	0.17	5.24
30	258	15.1	14	1.1	14.13
30	525	8.1	7.59	0.51	7.62
30	527	8.2	8.15	0.05	7.84

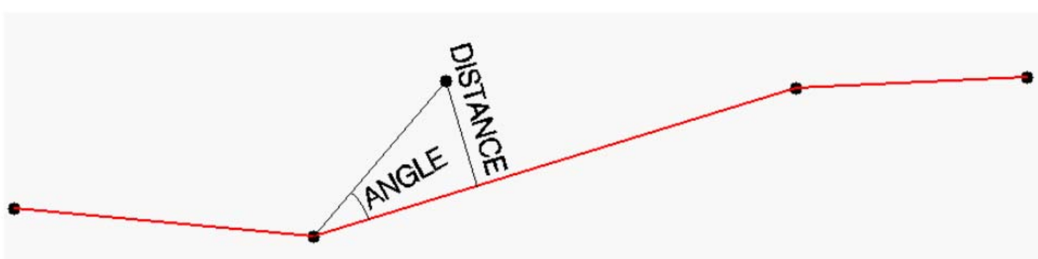
30	528	8.8	8.62	0.18	8.56
30	530	7.8	7.07	0.73	7.6

APPENDIX B: TERRASCAN SOFTWARE ALGORITHMS

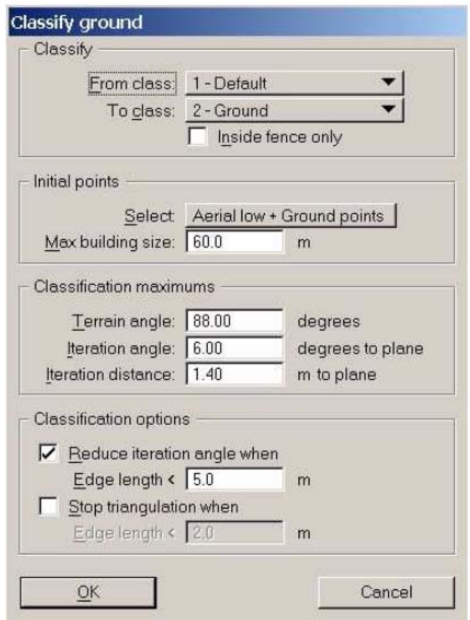
Ground Classification

Ground routine classifies ground points by iteratively building a triangulated surface model. The routine starts by selecting some local low points that are confident hits on the ground. You control initial point selection with the Max building size parameter. If maximum building size is 60.0 m, the application assumes that any 60 by 60 m area will have at least one hit on the ground (provided there are points around different parts of the area) and that the lowest point is a ground hit.

The routine builds an initial model from the selected low points. Triangles in this initial model are mostly below the ground with only the vertices touching ground. The routine then starts molding the model upwards by iteratively adding new laser points to it. Each added point makes the model following the ground surface more closely. Iteration parameters determine how close a point must be to a triangle plane for being accepted as ground point and added to the model. Iteration angle is the maximum angle between a point, its projection on triangle plane and the closest triangle vertex. Iteration distance parameter makes sure that the iteration does not make big jumps upwards when triangles are large. This helps to keep low buildings out of the model.



The smaller the Iteration angle, the less eager the routine is to follow changes in the point cloud (small undulations in terrain or hits on low vegetation). Use a small angle (close to 4.0) in flat terrain and a bigger angle (close to 10.0) in hilly terrain.



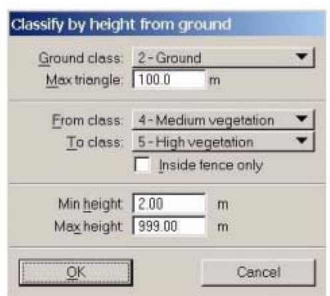
Setting:	**Effect:**
From class	Source class from which to classify points.
To class	Target class to classify points into.
Inside fence only	If on, points inside a fence or selected polygon are classified.
Select	Selection of initial ground points. If starting a new ground classification, use **Aerial low + Ground points**. Use **Current ground points** when you want to continue iteration in a fenced, previously classified area.
Max building size	Edge length of largest buildings.
Terrain angle	Steepest allowed slope in ground terrain.
Iteration angle	Maximum angle between point, its projection on triangle plane and closest triangle vertex. Normally between 4.0 and 10.0 degrees.
Iteration distance	Maximum distance from point to triangle plane during iteration. Normally between 0.5 and 1.5 m.
Reduce iteration angle when	If on, reduce eagerness to add new points to ground inside a triangle when every edge of triangle is shorter than **Edge length**. Helps to avoid adding unnecessary point density to the ground model and reduces memory requirement.
Stop triangulation when	If on, quit processing a triangle when every edge in triangle is shorter than **Edge length**. Helps to avoid adding unnecessary point density to the ground model and reduces memory requirement.

By Height from Ground:

By height from ground routine classifies points which are within a given height range compared to the ground points surface model. The routine requires that you have already classified ground points successfully.

This routine will build a temporary triangulated surface model from ground points and compare other points against the elevation of the triangulated model.

You might use this routine to classify points into different vegetation classes for preparing building classification, powerline processing or tree detection. As a result, the highest vegetation class should include all hits on the target objects of interest (building roofs, wires and towers, or trees).



Setting:	Effect:
Ground class	Point class into which ground points have been classified before.
Max triangle	Maximum length of a triangle edge in the temporary calculated surface model.
From class	Source class from which to classify points.
To class	Target class to classify points into.
Inside fence only	If on, points inside a fence or selected polygon are classified.
Min height	Start of height range above ground surface.
Max height	End of height range above ground surface.

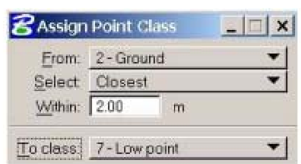
ASSIGN POINT CLASS:

Assign Point Class tool changes the class of one laser point. This tool is the fastest one if you locate just one badly classified point.

To classify one point:

1. Select the Assign Point Class tool.
2. Select settings.
3. Identify point to classify.

You can continue to step 2 if you want to change settings, or to step 3.This classifies the identified point. An editable model will immediately reflect the change



Setting:	Effect:
From class	Source class, only points from this class will be reclassified.
Select	Method how the software selects a point for reclassification: • Closest - the point next to the mouse click will be classified. • Highest - the highest point within the search radius will be classified. • Lowest - the lowest point within the search radius will be classified.
Within	Search radius.
To class	Target class into which points are classified.

Output a Control Report:

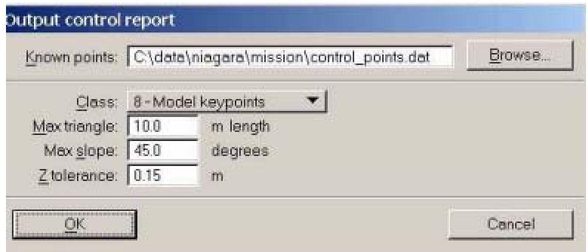
Output control report menu command creates a report of elevation differences between laser points and control points. This can be used to check the elevation accuracy of a laser data set and to calculate a correction value for improving the elevation accuracy of the laser points.

The control points have to be stored in a space delimited text file in which each row has four fields:identifier, easting, northing and elevation. the identifier field is normally a number but it may include non-numeric characters as well.

To create a control report:

1. Select Output control report command from Tools menu.

This opens the Output control report dialog:



2. Select a file that stores the control points.

3. Define settings and click OK.

This calculates the elevation differences and opens the Control report window.

Setting:	**Effect:**
Known points	Name and location of the file that stores the coordinates of the control points.
Class	Point class used for comparison with the control points.
Max triangle	Search radius around each known point.
Max slope	Maximum terrain slope for which an elevation difference will be computed.
Z tolerance	Normal elevation variation of laser points. This value is used only when computing the terrain slope so that small triangles will not exceed **Max slope**.