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A rigorous assessment of tree height measurements obtained using airborne lidar and conventional field methods

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Abstract. Tree height is an important variable in forest inventory programs but is typically time-consuming and costly to measure in the field using conventional techniques. Airborne light detection and ranging (lidar) provides individual tree height measurements that are highly correlated with field-derived measurements, but the imprecision of conventional field techniques does not allow for definitive assessments regarding the absolute accuracy of lidar tree height measurements and the relative influence of beam divergence setting (i.e., laser footprint size), species type, and digital terrain model (DTM) error on the accuracy of height measurements. In this study, we developed a methodology for acquiring accurate individual tree height measurements (<2 cm error) using a total station survey and used these measurements to establish the expected accuracy of lidar- and field-derived tree height measurements for two of the most ecologically and commercially significant species in western North America, Douglas-fir (*Pseudotsuga menziesii*) and ponderosa pine (*Pinus ponderosa*). Tree height measurements obtained from narrow-beam (0.33 m), high-density (6 points/m^2) lidar were more accurate (mean error ± SD = –0.73 ± 0.43 m) than those obtained from wide-beam (0.8 m) lidar (–1.12 ± 0.56 m). Lidar-derived height measurements were more accurate for ponderosa pine (–0.43 ± 0.13 m) than for Douglas-fir (–1.05 ± 0.41 m) at the narrow beam setting. Although tree heights acquired using conventional field techniques (–0.27 ± 0.27 m) were more accurate than those obtained using lidar (–0.73 ± 0.43 m for narrow beam setting), this difference will likely be offset by the wider coverage and cost efficiencies afforded by lidar-based forest survey.

Résumé. La hauteur des arbres est une variable importante dans les programmes d'inventaire forestier, mais la mesure de cette dernière sur le terrain à l'aide des techniques conventionnelles est chronophage et entraîne des coûts importants. Le lidar aéroporté fournit des mesures de la hauteur des arbres individuels qui sont fortement corrélées avec les mesures réalisées sur le terrain, mais l'imprécision des techniques conventionnelles de terrain ne permet pas de réaliser des évaluations finales en ce qui concerne la précision absolue des mesures lidar de la hauteur des arbres et l'influence relative de la divergence du faisceau (i.e. la dimension de l'empreinte laser), du type d'espèce et de l'erreur du modèle numérique de terrain (MNT) sur la précision des mesures de la hauteur. Dans cette étude, nous avons développé une méthodologie pour l'acquisition précise de mesures de la hauteur des arbres individuels (erreur de <2 cm) à l'aide des mesures d'un tachéomètre électronique et nous avons utilisé ces mesures pour établir la précision anticipée des mesures lidar et de terrain de la hauteur des arbres pour deux des espèces les plus significatives aux plans écologique et commercial dans l'ouest de l'Amérique du nord, le sapin de Douglas (*Pseudotsuga menziesii*) et le pin Ponderosa (*Pinus ponderosa*). Les mesures de la hauteur des arbres obtenues par lidar à faisceau étroit (0,33 m) et à haute densité (6 points/m^2) étaient plus précises (erreur type ± SD = –0,73 ± 0,43 m) que celles obtenues à l'aide du lidar (0,8 m) à faisceau large (–1,12 ± 0,56 m). Les mesures de la hauteur des arbres acquises par lidar étaient plus précises pour le pin Ponderosa (–0,43 ± 0,13 m) que pour le sapin de Douglas (–1,05 ± 0,41 m) dans le cas du faisceau étroit. Quoique les hauteurs d'arbre acquises à l'aide des techniques conventionnelles de terrain (–0,27 ± 0,27 m) étaient plus précises que celles obtenues à l'aide du lidar (–0,73 ± 0,43 m pour le faisceau étroit), cette différence serait éventuellement compensée par la couverture plus large et l'efficacité des coûts qu'offre l'inventaire forestier basé sur lidar.
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Introduction

Tree height is one of the more fundamental measurements in forest inventory and is a critical variable in the quantitative assessment of forest biomass, carbon stocks, growth, and site productivity. Individual tree height and stem diameter are the primary variables used in the estimation of tree and stand volume, and tree height at a given age is often used as an index of forest site quality (Schreuder et al., 1993). In the forestry context, *total height* is defined as the "vertical distance between the ground level and tip of the tree" (Husch et al., 1972).

Foresters have developed many different techniques for measuring individual tree heights over the years. The most direct method for measuring tree heights (up to 25 m) involves

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the use of height poles, which are reliable but susceptible to parallax error that can range as high as 10% (Schreuder et al., 1993). Due to the practical difficulties in measuring tree heights directly, foresters typically use indirect measurement techniques. Most indirect methods use measurements of angles to the tree base (θ) and treetop (ρ) and the horizontal distance (hd) to the tree stem to estimate the tree height using the following basic trigonometric formula (**Figure 1**):

$$h = \text{hd}(\tan \rho + \tan \theta) \qquad (1)$$

Distances are usually measured using a tape measure or electronic distance measurement device, such as a hand-held laser, and angles to the tree base and treetop are measured using a clinometer or an electronic vertical angle encoder. Hand-held laser rangefinders (with electronic measurement of distance and angles) are increasingly being used in forest inventory for measuring tree heights and can yield measurements with errors of 1%–2% (Wing et al., 2004). However, this method is very difficult, or even impossible, to implement in closed stands, where the treetops are not easily visible. For this reason, measurement of tree height is usually one of the more time-intensive, and therefore expensive, components of a forest inventory program.

The emergence of airborne lidar remote sensing in recent years has provided an economical and efficient means of obtaining accurate measurements of individual tree heights over large areas of forest (St. Onge et al., 2003; Reutebuch et al., 2005). Lidar remote sensing generates highly accurate three-dimensional (3D) measurements of the forest canopy surface, and individual tree crowns can be detected and measured when lidar is acquired at a high density (more than 4 points/m^2). The capability of lidar to accurately measure a small feature on the canopy surface (such as a treetop) is dependent upon a number of factors, including the size and reflectivity of the target, sampling density, pulse diameter, and peak-detection method implemented in the system hardware (Baltsavias, 1999). For a given system, the user typically has total control over the sampling density, limited control over the pulse diameter, and little control over other factors. The sampling density is entirely a function of the pulse rate of the system, the scanning angle and pattern, and the flight parameters (flying height and speed). Other considerations, such as cost and collection scheduling, usually determine the maximum practical sampling density for a given project. Many systems allow for limited adjustment of the beam divergence of the laser pulse, which, along with flying height, will determine the diameter of the laser "footprint" on the canopy surface. Although use of a larger laser footprint will theoretically increase the probability of hitting the topmost point on a tree crown, this is offset by the lower power per unit area for this setting (i.e., the same amount of laser power distributed over a larger footprint), decreasing the likelihood of recording a reflection associated with a small treetop. As lidar is increasingly becoming a viable tool in forest resource management, there is a need for a rigorous assessment of the expected accuracy of lidar tree height measurements in the forest inventory context, with a comparison to alternative field techniques.

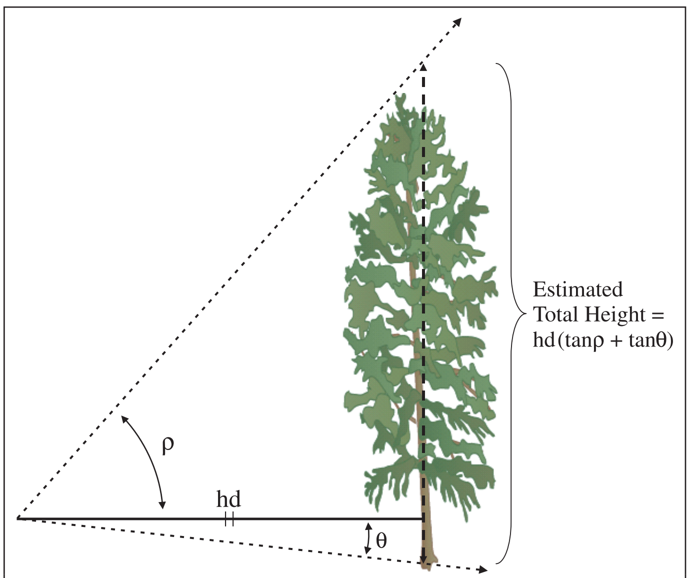

Figure 1. Conventional method of measuring total tree height in the field using trigonometric principles.

Numerous previous studies have shown a high correlation between tree measurements acquired from lidar and those acquired using traditional field methods (**Table 1**). Hyyppä et al. (2000) evaluated lidar tree height measurements in a Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) forest in Finland through a comparison with field measurements. Lidar data were acquired with a TopoSys-1[2] (TopoSys GmbH, Biberach, Germany) system at a density of 24 points/m^2, and field tree height measurements were acquired using a tacheometer with a stated accuracy of 0.5–1.0 m. Hyyppä et al. reported a bias in the lidar tree height measurements of –0.14 m and root mean squared error (RMSE) of 0.98 m. Persson et al. (2002) investigated the effects of footprint diameter on lidar-derived tree height measurements in a Norway spruce and Scots pine forest in Sweden. In this study, lidar data were acquired with a SAAB TopEye system (SAAB Survey Systems, Jonkoping, Sweden) mounted on a helicopter at two different flying heights and four different beam divergence settings, resulting in footprint diameters of 0.26, 0.52, 1.04, 2.08, and 3.68 m. The distance between points was 0.44 m in scan direction and 0.48 m in flight direction. Field tree heights were measured using a Suunto hypsometer (Suunto Inc., Vantaa, Finland) with an error of 0.4–0.8 m. This study found that the error in tree height measurements was not significantly affected by beam size (RMSE of 0.65 for 0.26 m footprint diameter and 0.76 m for 3.68 m footprint diameter). Persson et al. note that a

[2] Use of trade or firm names in this publication is for reader information and does not imply endorsement by the US Department of Agriculture of any product or service.

significant portion of this RMSE could be caused by errors in the field height measurements. In addition, this study found that the mean (horizontal) positional difference between lidar- and field-based tree stem locations was 0.51 m. Næsset and Økland (2002) investigated the utility of lidar for estimating tree height and several crown properties within a boreal nature reserve in Norway dominated by Norway spruce. The lidar data used in this study were acquired with an Optech ALTM 1210 system (Optech Incorporated, Vaughan, Ont.) at a density of 0.6–2.3 points/m^2 and with a footprint diameter of 0.18 m. Tree heights were measured in the field with a Haglöf Vertex hypsometer (Haglöf, Langsele, Sweden). Through a stepwise regression procedure, Næsset and Økland found that maximum first pulse laser height was the best predictor of individual tree height and report a mean difference between predicted and ground-truth height measurements of 0.18 m, with a standard deviation of 3.15 m. Brandtberg et al. (2003) evaluated lidar tree heights acquired in leaf-off conditions within an eastern deciduous forest in the United States. The lidar data were acquired with a SAAB TopEye system mounted on a helicopter, resulting in a footprint diameter of 0.1 m and a sampling density of 12 points/m^2. The field height measurements were acquired using a laser rangefinder and a clinometer (there was a single growing season between collection of lidar and field measurements, but Brandtberg et al. note that this will have little effect in this mature forest). This study reported an overall standard error of 1.1 m for lidar tree height measurements in comparison to field heights. Gaveau and Hill (2003) acquired accurate measurements of canopy surface height in a leaf-on deciduous forest in the eastern United Kingdom using a total station survey and reported that the lidar point-sample data, acquired at a density of approximately 5 points/m^2 with a footprint diameter of 0.25 m, underestimated canopy surface height by 0.91 m in shrub canopies and 1.27 in tree canopies. Hirata (2004) investigated the effect of footprint size and sampling density on lidar tree height measurements in a Japanese cedar (*Cryptomeria japonica*) stand. Lidar data were acquired with an Optech ALTM 1025A/1225 system mounted on a helicopter platform at different flying heights, leading to varying laser footprint diameters (0.3, 0.6, and 1.2 m) and sampling densities (24.8, 10.1, and 7.5 points/m^2). Field measurements were acquired with a Haglöf handheld laser instrument. Hirata found that lower lidar sampling densities led to increased underestimation of field-measured tree heights. This study also found that the use of a larger footprint diameter led to overestimation of canopy surface heights. Yu et al. (2004) investigated the effects of flying height and footprint size on tree height estimation in a boreal forest in Finland composed of Norway spruce, Scots pine, and birch (*Betula verrucosa* and *Betula pubescens*, in leaf-off condition). Lidar data were acquired with a TopoSys Falcon lidar system at three different altitudes, resulting in sampling densities of 10, 5, and 2.5 points/m^2 and laser footprint sizes of 0.20, 0.40, and 0.75 m. Yu et al. found that underestimation of tree height (and standard deviation) increased with higher flying heights, probably because of lower sampling density and lower power of the received signal. The degree of underestimation did depend on species, however, with birch less affected than spruce or pine. This study also found that footprint size did not significantly influence height estimates. At a pulse density of 5 points/m^2, this study reported accuracies of –0.20 ± 0.74 m (mean ± SD) for pine, –0.09 ± 0.81 for spruce, and –0.09 ± 0.94 for birch, although these results include a difference due to 1–2 years of growth between field and lidar measurements. Maltamo et al. (2004) compared lidar-derived tree height measurements with highly accurate field measurements of annual shoots on 29 Scots pine trees acquired directly with a fiberglass rod or, in the case of taller trees, indirectly (using trigonometric principles) using a tacheometer and theodolite–distometer. Maltamo et al. reported that lidar underestimated tree heights by 0.65 m, with a standard error of 0.49 m. Rönnholm et al. (2004) developed an approach to directly evaluate the accuracy of lidar-derived tree height measurements using terrestrial photogrammetry. This study used lidar acquired with TopoSys Falcon (10 points/m^2) and SAAB TopEye (1–5 points/m^2) systems, with measurements of tree heights for five trees obtained using a tacheometer (but with a 2 year difference between field and lidar data collections, leading to an estimated growth of 0.2 m). Leaf-on birch tree heights (measured with TopEye) were underestimated by 1.46 m, spruce tree heights (measured with TopoSys) by 1.28, and aspen tree heights (*Populus tremula*, in leaf-off condition) (TopoSys) by 0.76 and 0.94 m. In a comparison of the terrestrial photogrammetric measurements and the lidar data, the authors found that the highest point on a spruce tree was still not measured, even at a sampling density of 50 points/m^2. McGaughey et al. (2004) compared lidar-derived tree height measurements with field measurements acquired with an Impulse handheld laser instrument in a Pacific Northwest forest composed of Douglas-fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*) and reported an error (lidar – field) of 0.29 ± 2.23 m.

Although the dominant source of error in lidar tree height measurement is due to the difficulty in measuring treetop location, errors in the lidar terrain measurements could also have a significant effect on lidar tree height measurements. Leckie et al. (2003) report that errors in the lidar-derived measurement of tree base elevation due to ground vegetation and terrain microrelief could easily introduce up to 0.5 m of variability in height measurements. Although errors in terrain models derived from high-density data are unlikely to introduce errors greater than 0.30 m (Reutebuch et al., 2003), it is important to recognize their contribution to the overall error budget in lidar tree height measurement. In addition, it is possible that the quality of the digital terrain model (DTM) is reduced in the local area directly beneath a tree crown (where the lidar-derived tree base elevation is measured) because of a lower number of pulses reaching the ground and the influence of the tree stem.

Hyyppä et al. (2004) recognized that the accuracy of conventional field inventory techniques may not be sufficient for detailed evaluation of the error in lidar tree height measurement and stated that the processes underlying lidar height measurement error are therefore still not adequately understood. The objectives of this study were to (*i*) perform an assessment of the error in lidar-derived tree height measurements for two of the most ecologically and commercially significant tree species of western North America, Douglas-fir (*Pseudotsuga menziesii*) and ponderosa pine (*Pinus ponderosa*); (*ii*) evaluate the effect of beam divergence on the error; and (*iii*) compare lidar measurements with conventional field measurements. This approach uses a total station survey to establish a measurement for the 3D coordinate of the treetop and tree base and provides an estimate of the accuracy of these measurements. Using this total station survey as the basis of comparison, we are able to separate the effects of treetop measurement error (vertical and horizontal), terrain measurement error, and laser pulse diameter on the accuracy of lidar tree height measurements, and we provide a comparison with field-based height measurements for these two important tree species.

Data and methods

Lidar data

Lidar data were collected over two relatively flat study areas within Fort Lewis Military Reservation, Washington State, USA, on 19–21 September 2005 and 17 March 2006 with an Optech ALTM 3100 lidar system mounted in a Cessna Caravan aircraft. The locations of the study areas are shown in **Figure 2**.

Area 1 is approximately 3 ha in extent and is composed primarily of ponderosa pine with some young Douglas-fir. Area 2 is approximately 4 ha in extent and is composed of open-grown mature Douglas fir. Specifications for the lidar collections are shown in **Table 2**. The 2005 lidar data were acquired with a narrow beam divergence setting (0.3 mrad, corresponding to a 0.33 m footprint), the 2006 lidar data were acquired with a wide beam divergence setting (0.8 mrad, corresponding to a 0.8 m footprint), and the 2006 wide-beam data were acquired at a slightly lower flying height (1000 m versus 1100 m) to increase the signal-to-noise ratio for the laser returns. All other specifications were essentially the same between the lidar acquisitions. The nominal horizontal accuracy (1σ) of this system is 50–55 cm, and the nominal vertical accuracy (1σ) is 15 cm (Optech Incorporated, 2006). The growing season for Douglas-fir in this area is early May to the middle of July, and the growing season for ponderosa pine lasts from mid-April to August, so there was no height growth for either of these species between the lidar acquisitions. Lidar data were provided in the Universal Transverse Mercator (UTM) zone 10 North American datum of 1983 (NAD 83) projection, with orthometric North American vertical datum of 1988 (NAVD 88) heights.

Generation of lidar-derived digital terrain model (DTM)

The lidar point cloud was filtered to identify ground returns. The filtering method is the authors' adaptation of the method developed by Kraus and Pfeifer (1998). The method is iterative and begins by computing an initial surface model using the

Table 1. Summary of results from previous assessments of lidar-derived individual tree height measurements.

Species type	Location	Laser pulse density (points/m^2)	Laser footprint diameter (m)	Field height estimation technique	Relationship–difference between lidar- and field-measured tree heights (m)	Reference
Norway spruce, Scots pine	Finland	24	0.4	Tacheometer	Mean = −0.14; RMSE = 0.98	Hyyppä et al. (2000)
Norway spruce, Scots pine	Sweden	4.7	0.26, 0.52, 1.04, 2.03, 3.68	Suunto hypsometer	RMSE (at different footprints) = 0.65, 0.72, 0.64, 0.64, 0.76	Persson et al. (2002)
Norway spruce, Scots pine	Norway	0.6–2.3	0.18	Vertex hypsometer	Mean ± SD = 0.18 ± 3.15	Næsset and Økland (2002)
Leaf-off deciduous	Eastern US	12	0.1	Laser rangefinder and clinometer	RMSE = 1.1	Brandtberg et al. (2003)
Leaf-on deciduous	Eastern UK	5	0.25	Total station survey	Mean = −0.91 (shrub), −1.27 (trees)	Gaveau and Hill (2003)
Norway spruce (S), Scots pine (P), birch (B)	Finland	5	0.2	na	Mean ± SD = −0.20 ± 0.74 (P), −0.09 ± 0.81 (S), −0.09 ± 0.94 (B)	Yu et al. (2004)
Scots pine	Finland	10	0.2	Fibreglass rod, tacheometer, theodolite–distometer	Mean ± SD = −0.65 ± 0.49	Maltamo et al. (2004)
Leaf-on birch (B), spruce (S), aspen (A)	Finland	10 (S, A), 1–5 (B)	0.2 (S, A), 0.20–0.55 (B)	Tacheometer	−1.46 (B), −1.28 (S), −0.76 and −0.94 (A)	Rönnholm et al. (2004)
Douglas-fir, western hemlock	Northwestern US	4	0.4	Impulse hand-held laser	Mean ± SD = 0.29 ± 2.23	McGaughey et al. (2004)

Note: na, not available.

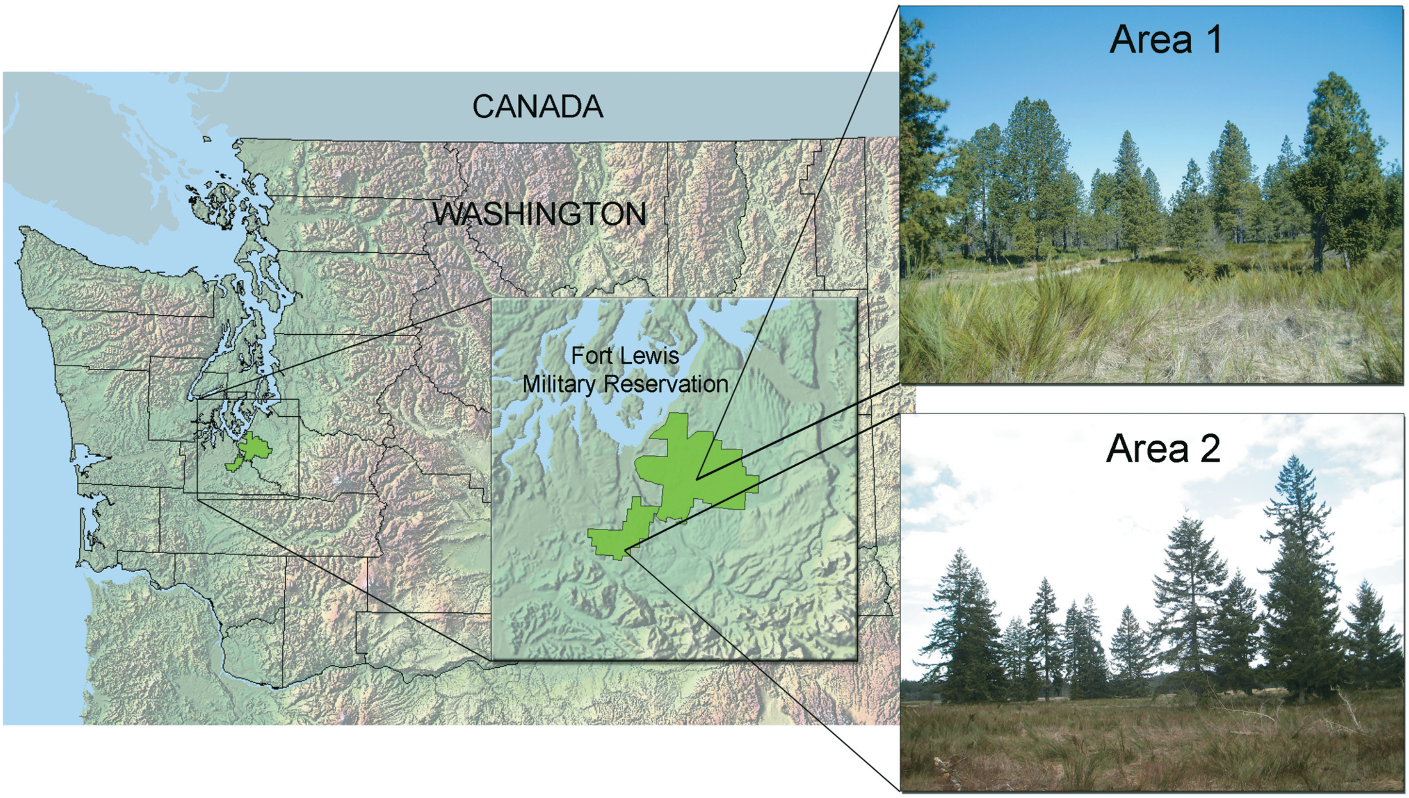

Figure 2. Location of study areas, Fort Lewis Military Reservation, Washington State.

Table 2. Flight parameters and system settings for 2005 and 2006 lidar collections.

	2005 Lidar	2006 Lidar
Scan angle (°)	14	10
Flying height above ground level (AGL) (m)	1100	1000
Scan pulse rate (kHz)	71	71
Scan width (m)	>548	>345
Sampling density (pulses/m^2)	6	6
Beam divergence (laser footprint diameter) (mrad)	0.3 (0.33 m)	0.8 (0.80 m)

average elevation for all returns within a 1 m × 1 m grid cell. This intermediate surface is influenced equally by ground and vegetation returns. For each iteration, residuals are computed as the difference between the return elevation and an elevation interpolated from the intermediate surface using the X,Y location of the return. Ground returns are more likely to be below the surface and thus have negative residuals, whereas vegetation returns are more likely to be close to or above the surface, resulting in small negative or positive residuals. The residuals (v_i) are used to compute weights (p_i) for each return using the weight function from Kraus and Pfeifer:

$$p_i = 1.0 \qquad v_i < g \tag{2}$$

$$p_i = \frac{1}{1 + [a(v_i - g)^b]} \qquad g < v_i \le g + w \tag{3}$$

$$p_i = 0.0 \qquad g + w < v_i \tag{4}$$

with $a = 1.0$, $b = 4.0$, $g = 0.0$, and $w = 0.5$. The weights cause the surface computed at the end of the iteration to drop towards the true ground surface. Cells with no ground returns are flagged as a hole in the intermediate surface model and are filled by interpolating from surrounding cell values. To help eliminate vegetation returns isolated during the iteration, the final procedure for each iteration smooths the intermediate surface using a mean filter operating over a 7 pixel × 7 pixel window. Without the smoothing, the algorithm classifies some vegetation returns as ground returns in areas where there are no true ground returns, such as under dense vegetation. For the terrain and vegetation conditions in this study, five iterations were sufficient to remove returns from vegetation while preserving returns that define features such as edges of roads, ditches along roads, and stream banks. The authors' experience with this algorithm indicates that additional iterations simply remove returns that define such features, and the resulting final surface is unnecessarily smoothed. After the final iteration, all points below or within 15 cm of the intermediate surface are saved and used to create the final ground surface model by averaging the elevation of the returns within each 1 m × 1 m grid cell. The 15 cm value corresponds to the vertical error in the return elevations provided by the lidar contractor. Using the average of all bare-ground returns in each cell to create the final surface acknowledges the presence of this error in the lidar returns and results in a ground surface free of the high-frequency noise that would be present with more complex interpolation methods. Cells with no returns are flagged as holes in the surface and are filled by interpolating elevations from surrounding cells. The RMSE for the ground returns (ground return elevation minus the final surface model elevation interpolated for the same location) is about 6 cm for the areas used in this study.

To evaluate the absolute accuracy of the final surface model, we compared elevations for 89 points obtained during a first-order survey of field plot locations with elevations interpolated from the final surface model. The average difference (survey point elevation minus final surface model elevation interpolated for the same location) was 13.7 cm, with a standard deviation of 8.7 cm (RMSE = 16.2 cm). Despite the downward bias evident in the final surface model, we feel the model accurately represents the ground surface, especially considering that the reported nominal vertical accuracy for the laser scanner used to acquire the data is 15 cm (1σ).

Total station survey of individual trees

A local survey network was established to acquire highly accurate measurements of individual treetops and bases from 17 to 22 November 2005. A high-order Topcon ITS-1 total station surveying instrument (Topcon Positioning Systems Inc., Livermore, Calif.), with a 30× sighting scope and a nominal accuracy of 2 s (1σ) for angle measurements and 2 mm (1σ) for horizontal distance measurements, was used to establish the local survey network. The total station was set up on three hubs in area 1 and six hubs in area 2, and the distance, horizontal angle, and vertical angle were established between each hub. The horizontal and vertical angles to the visible treetop of every nearby tree were measured from each hub, and the horizontal distance and horizontal angle to a vertical prism rod located at the base of the tree were shot (**Figure 3**).

Each shot from a hub to a treetop will establish a 3D vector, and with two or more shots, the 3D coordinate of the treetop location can be estimated by the point of intersection for the vectors (**Figure 3**). As there will never be an exact point of intersection, the most probable location of the treetop can be estimated through a least-squares solution. A 3D line can be defined by two points $\boldsymbol{s}_1 = (x_1, y_1, z_1)$ and $\boldsymbol{s}_2 = (x_2, y_2, z_2)$, and a vector along this line can be parameterized as

$$\boldsymbol{v} = \boldsymbol{s}_1 + (\boldsymbol{s}_2 - \boldsymbol{s}_1)t \tag{5}$$

where t is the parameter of the line (**Figure 4**) (Weisstein, 2006). In the context of this project, the point $\boldsymbol{s}_1$ is the location of the total station instrument, $\boldsymbol{s}_2$ is the sighted treetop (measured with some error d), and $\boldsymbol{s}_0 = (x_0, y_0, z_0)$ is the true 3D coordinate of the treetop.

The squared distance between a point on this line specified by t and the point $\boldsymbol{s}_0$ is given by

$$d^2 = |(\boldsymbol{s}_1 - \boldsymbol{s}_0) + (\boldsymbol{s}_2 - \boldsymbol{s}_1)t|^2 \tag{6}$$

and the minimum distance to this point from the line is given by setting $\partial d^2/\partial t = 0$ and solving for t to yield

$$t = -[(\boldsymbol{s}_1 - \boldsymbol{s}_0) \cdot (\boldsymbol{s}_2 - \boldsymbol{s}_1)]/|(\boldsymbol{s}_2 - \boldsymbol{s}_1)|^2 \tag{7}$$

The minimum squared distance d^2 is then given by replacing t in the previous equation to yield

$$d^2 = [|(\boldsymbol{s}_1 - \boldsymbol{s}_0)|^2 |(\boldsymbol{s}_2 - \boldsymbol{s}_1)|^2 - [(\boldsymbol{s}_1 - \boldsymbol{s}_0) \cdot (\boldsymbol{s}_2 - \boldsymbol{s}_1)]^2]/|(\boldsymbol{s}_2 - \boldsymbol{s}_1)|^2 \tag{8}$$

When more than two vectors are established between the total station locations and the treetop (see **Figure 3**), we can develop a least-squares solution for the 3D coordinate of the treetop. To find the 3D treetop point $\boldsymbol{s}_0$ that minimizes the sum of the squared distances to each of n vectors (i.e., the most probable treetop location), we solve the following system of nonlinear equations:

$$\frac{\partial \sum_{i=0}^{n} d_i^2}{\partial x_0} = \sum_{i=0}^{n} \left\{ \frac{-2(x_{1i} - x_{2i})[(x_{1i} - x_0)(x_{2i} - x_{1i}) + (y_{1i} - y_0)(y_{2i} - y_{1i}) + (z_{1i} - z_0)(z_{2i} - z_{1i})] - 2(x_{1i} - x_0)[(x_{2i} - x_{1i})^2 + (y_{2i} - y_{1i})^2 + (z_{2i} - z_{1i})^2]}{(x_{2i} - x_{1i})^2 + (y_{2i} - y_{1i})^2 + (z_{2i} - z_{1i})^2} \right\} = 0 \tag{9}$$

$$\frac{\partial \sum_{i=0}^{n} d_i^2}{\partial y_0} = \sum_{i=0}^{n} \left\{ \frac{-2(y_{1i} - y_{2i})[(x_{1i} - x_0)(x_{2i} - x_{1i}) + (y_{1i} - y_0)(y_{2i} - y_{1i}) + (z_{1i} - z_0)(z_{2i} - z_{1i})] - 2(y_{1i} - y_0)[(x_{2i} - x_{1i})^2 + (y_{2i} - y_{1i})^2 + (z_{2i} - z_{1i})^2]}{(x_{2i} - x_{1i})^2 + (y_{2i} - y_{1i})^2 + (z_{2i} - z_{1i})^2} \right\} = 0 \tag{10}$$

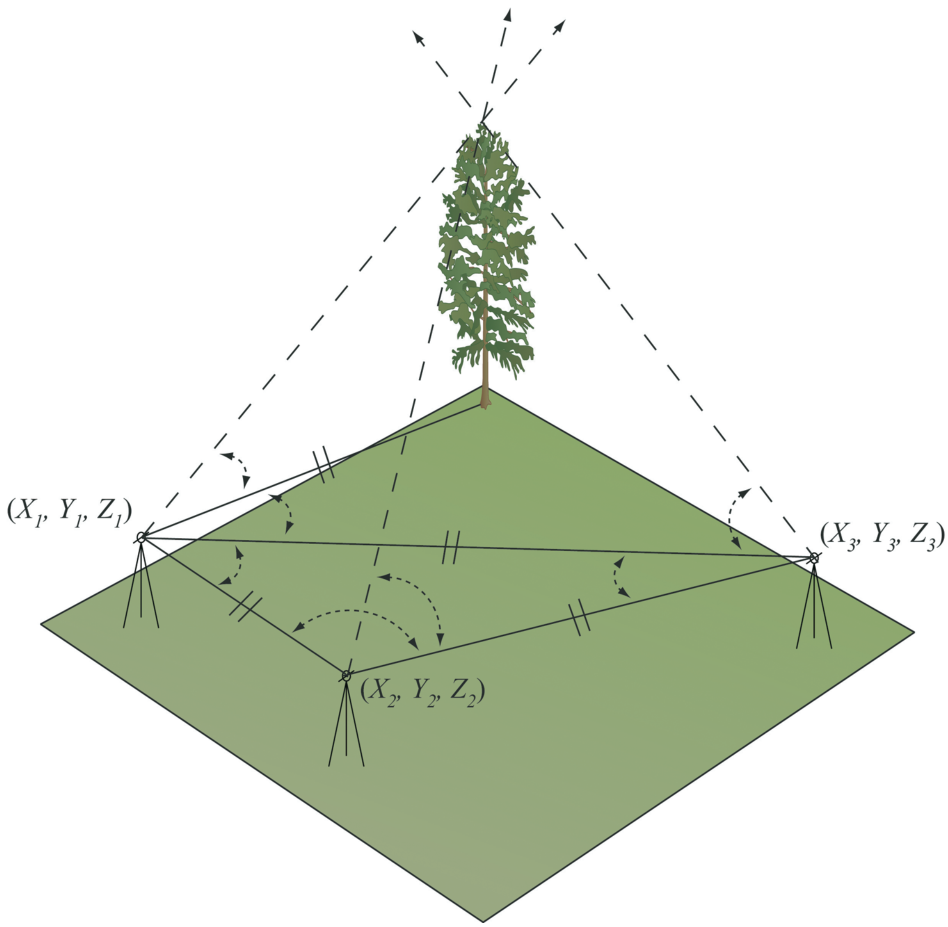

Figure 3. Measurement of treetop and base location via total station survey. Broken lines indicate angular measurements only; solid lines indicate distance and angular measurements.

$$\frac{\partial \sum_{i=0}^{n} d_i^2}{\partial z_0} = \sum_{i=0}^{n} \left\{ \frac{-2(z_{1i} - z_{2i})[(x_{1i} - x_0)(x_{2i} - x_{1i}) + (y_{1i} - y_0)(y_{2i} - y_{1i}) + (z_{1i} - z_0)(z_{2i} - z_{1i})] - 2(z_{1i} - z_0)[(x_{2i} - x_{1i})^2 + (y_{2i} - y_{1i})^2 + (z_{2i} - z_{1i})^2]}{(x_{2i} - x_{1i})^2 + (y_{2i} - y_{1i})^2 + (z_{2i} - z_{1i})^2} \right\} = 0 \tag{11}$$

Because of the nonlinear nature of these equations, this system cannot be solved analytically. Therefore, a globally convergent Newton–Raphson algorithm was used to derive the solution numerically (Press et al., 1992). The RMSE of the solution is then given by

$$\text{RMSE} = \sqrt{\frac{\sum_{i=0}^{n} d_i^2}{n}} = \sqrt{\frac{\sum_{i=0}^{n} \frac{|(\mathbf{s}_{1i} - \mathbf{s}_0)|^2 |(\mathbf{s}_{2i} - \mathbf{s}_{1i})|^2 - [(\mathbf{s}_{1i} - \mathbf{s}_0) \cdot (\mathbf{s}_{2i} - \mathbf{s}_{1i})]^2}{|(\mathbf{s}_{2i} - \mathbf{s}_{1i})|^2}}{n}} \tag{12}$$

This method will therefore provide an estimate of the error (RMSE) in the measurement of each treetop coordinate. In this study, a total of 37 trees (33 ponderosa pine, four Douglas-fir) were measured in area 1, and 34 trees (all Douglas-fir) in area 2. Most trees were visible from three or more hub locations. To ensure that the tree height measurements acquired via the total station methodology were extremely accurate, only trees whose top locations were measured with negligible error (RMSE < 5 cm) were used in the analysis (30 ponderosa pine, 29 Douglas-fir). The mean height (±SD) of the trees was 25.7 ± 9.8 m (Douglas-fir) and 16.5 ± 5.6 m (ponderosa pine). The average RMSE for the treetop measurements used in this study was 1.8 cm. The 3D coordinates for each tree base location were simply obtained using the measurements of horizontal distance, horizontal angle, and vertical angle from the total station to a prism located at the tree base.

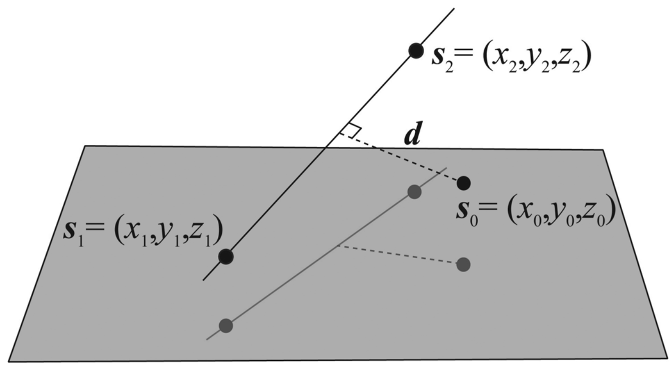

Figure 4. Minimum distance between a point and line in three dimensions. Adapted from Weisstein (2006).

The total station survey provided 3D coordinates (*x*, *y*, *z*) for the treetop and base locations in a local coordinate system. To register these locations to the lidar data, the position of each total station hub was established with a Javad Maxor dual-frequency and GLONASS-enabled global positioning system (GPS) unit (Javad Navigation Systems, San Jose, Calif.). These positions were differentially corrected using a nearby continuously operating reference station (CORS) as a base station. The estimated accuracy (1σ) of the GPS-derived horizontal positions was 3.4 mm. Due to the slight (~0.18 m) vertical offset between the two lidar datasets (2005 and 2006 acquisitions), the total station survey measurements were registered to each lidar dataset independently. To obtain vertical ground-control points at each site, the vertical angles, horizontal angles, and distance were measured to numerous points in bare, flat areas within each site, usually along roads (eight points in area 1, 16 points in area 2). These vertical control points, along with the horizontal control at the hubs obtained from the survey-grade GPS measurements, were used to transform the local coordinates established in the total station survey to the UTM (zone 10) NAD 83, NAVD 88 coordinate system via a 3D conformal transformation (Wolf and Ghilani, 1997). This transformation estimates seven parameters (three rotations (along the *x*, *y*, and *z* axis), three translations, and one scale factor) in a least-squares solution. The average of the residuals for the transformation in all four cases (two lidar datasets at each study area) was approximately 1 cm. This transformation was applied to all tree measurements acquired in the total station survey, yielding 3D coordinates (*X*, *Y*, *Z*) of the treetop and tree base in the same coordinate system as that of the lidar data.

Measurement of lidar-derived tree heights in FUSION software

Each lidar dataset was imported into the FUSION software package (Remote Sensing Applications Center, USDA Forest Service, Salt Lake City, Utah), which allows for interactive measurement of features within a 3D lidar point cloud (McGaughey et al., 2004). In this software package, the lidar point cloud associated with each tree measured in the field can be isolated and displayed in a 3D perspective view (**Figure 5**).

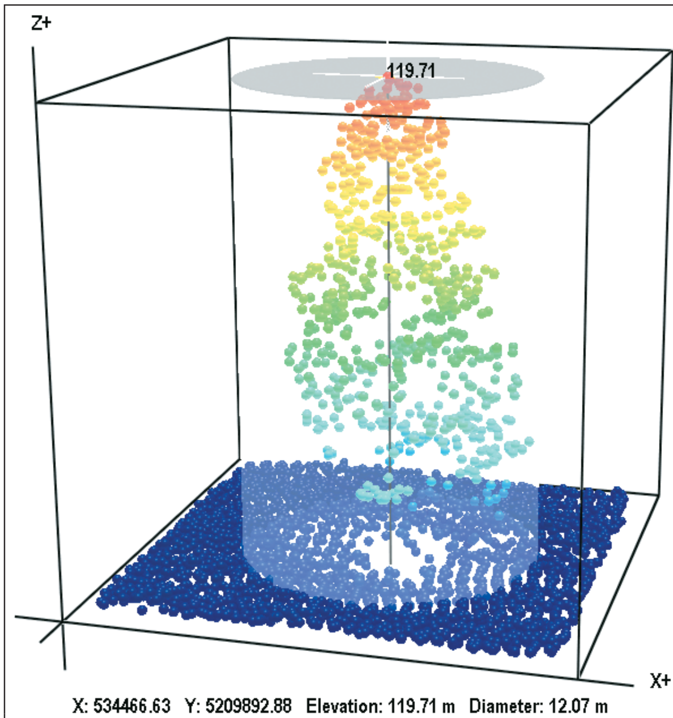

Figure 5. Manual measurement of lidar-derived treetop coordinates in FUSION software.

The coordinate of the lidar point with the highest elevation for each tree was recorded and stored in a data file. The height of these points was then determined by subtracting the elevation of the DTM below the lidar point. The DTM elevation at the base of the tree was computed via bilinear interpolation. This procedure provided the lidar-derived 3D coordinates of the treetops and tree bases for all trees measured in the total station survey.

Measurement of tree heights using field methods

The height of each tree was also measured using conventional field techniques. An Impulse 100 hand-held laser rangefinder (Laser Technology Inc., Centennial, Colo.) with electronic clinometer was used to measure the horizontal distance to the tree stem and angles to the tree base and treetop, and the instrument provides an estimate of tree height using trigonometry (see **Figure 1**). Three height measurements were averaged for each tree.

Results

Tree heights measured in the total station survey were compared with tree heights measured using both wide- and narrow-beam lidar data. As mentioned previously, the error in lidar tree height measurements is a combination of error due to treetop detection and error in the DTM at the base of the tree. The proportion of this total error associated with treetop

Table 3. Summary of error (mean ± SD, in m) in lidar-derived tree height measurements, narrow beam divergence setting (0.3 mrad, corresponding to a 0.33 m footprint).

Species (*n*)	Height error	Vertical error in treetop measurement	Vertical error in tree base measurement
Douglas-fir (29)	–1.05±0.41	–1.09±0.32	–0.04±0.16
Ponderosa pine (30)	–0.43±0.13	–0.40±0.11	0.03±0.10
All trees (59)	–0.73±0.43	–0.74±0.42	–0.004±0.14

Table 4. Summary of error (mean ± SD, in m) in lidar-derived tree height measurements, wide beam divergence setting (0.8 mrad, corresponding to a 0.8 m footprint).

Species	Height error	Vertical error in treetop measurement	Vertical error in tree base measurement
Douglas-fir	–1.49±0.56	–1.60±0.47	–0.10±0.18
Ponderosa pine	–0.77±0.24	–0.85±0.20	–0.08±0.14
All trees	–1.12±0.56	–1.20±0.52	–0.09±0.16

measurement and DTM error was also calculated for each tree. Summaries of the lidar measurement errors for each beam divergence setting, separated by species type, are shown in **Tables 3** and **4**. The overall mean error of the field height measurements was –0.27 ± 0.27 m (mean ± SD), with an error of –0.37 ± 0.29 m (mean ± SD) for Douglas-fir and –0.16 ± 0.21 m for ponderosa pine. Box plots of the height error for different beam sizes, different species, and field versus lidar are shown in **Figure 6**.

A Welch *t*-test of the difference between means showed that the bias in tree heights measured with narrow-beam lidar was significantly lower than that from wide-beam lidar ($P < 0.001$). The difference between mean height errors for Douglas-fir and ponderosa pine was also significant for both beam divergence settings ($P < 0.001$). The difference between mean height errors from narrow-beam lidar and conventional field methods was also significant ($P < 0.001$).

In addition, the horizontal error (distance, in x and y directions, between treetop location measured in lidar versus total station survey) was calculated for each tree to assess the accuracy of lidar treetop detection for different beam divergence settings and for both species (**Figures 7** and **8**).

Discussion

The results indicate that high-density (6 points/m^2), narrow-beam lidar is significantly more accurate than wide-beam lidar for measuring individual tree heights. Both systematic and random components of the tree height measurement error (given by the mean and standard deviation of the error, respectively) were lower for narrow-beam lidar than for wide-beam lidar (**Tables 3** and **4**). Although the wide-beam lidar may afford more comprehensive coverage of the canopy surface, this advantage is more than offset by the fact that the power of the lidar pulse is spread out over a larger area, leading to a lower signal-to-noise ratio for the returning lidar signal. Given that the returned signal from a small terminal leader of a conifer tree is relatively weak, it is assumed that many of the returns from the treetops in wide-beam lidar do not exceed the noise threshold and are therefore not recorded by the system. This was at least partially confirmed by the range of reflection intensities observed in the two datasets. The range of intensities for the narrow-beam lidar data was approximately seven times greater than that for the wide-beam lidar, which roughly corresponds to the ratio between the areas covered by the two beam sizes (wide beam covers 5.8 times more area than narrow

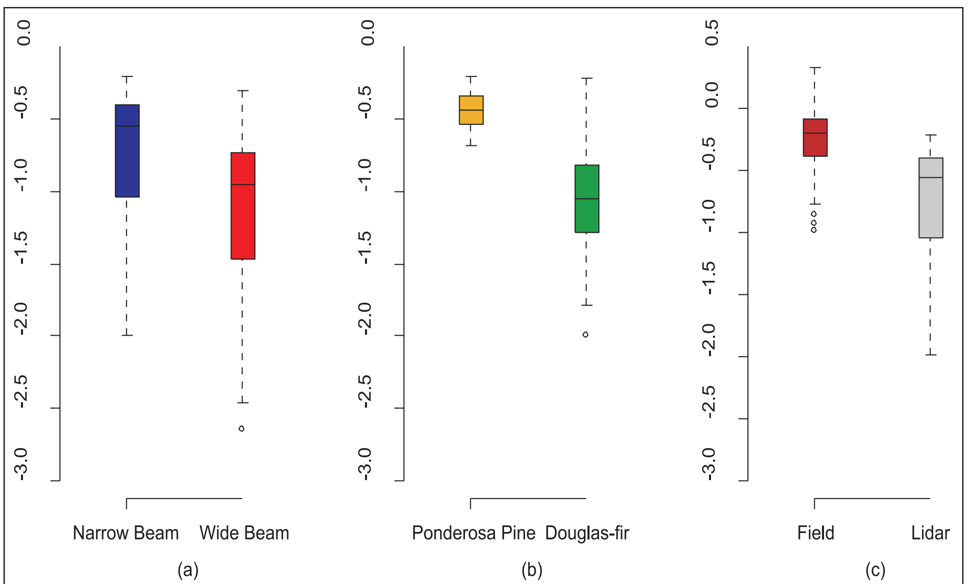

Figure 6. Box plots of height error for (a) narrow-beam versus wide-beam lidar, (b) species (narrow-beam lidar), and (c) field versus lidar (narrow-beam lidar).

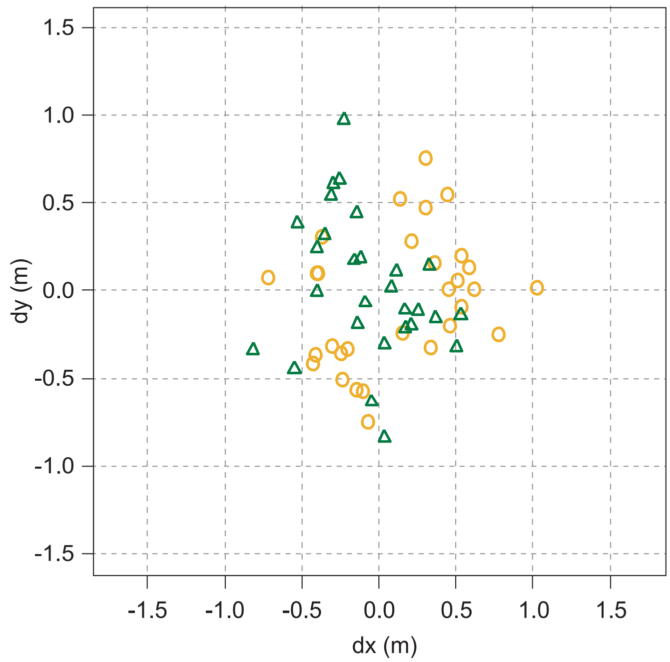

Figure 7. Horizontal error in lidar treetop measurement, narrow beam divergence setting. Green triangles denote Douglas-fir, and brown circles denote ponderosa pine. The mean positional error was 0.45 m (Douglas-fir), 0.56 m (ponderosa pine), and 0.50 m (all trees).

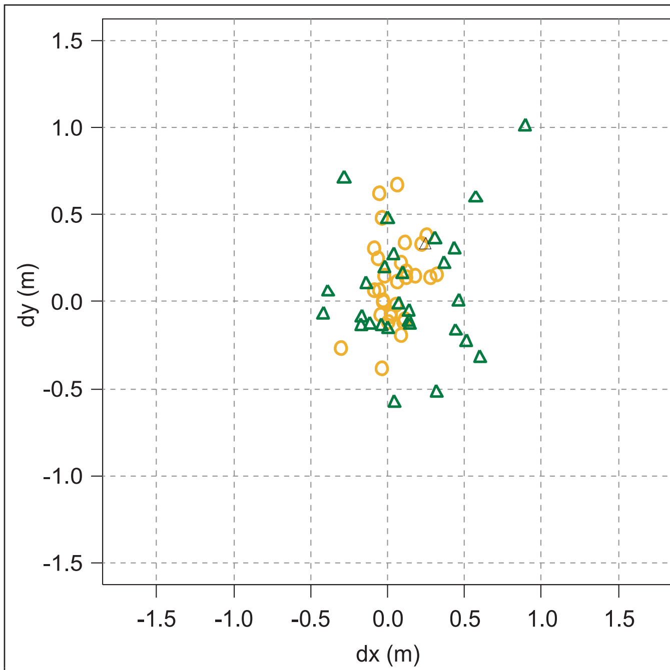

Figure 8. Horizontal error in lidar treetop measurement, wide beam divergence setting. Green triangles denote Douglas-fir, and brown circles denote ponderosa pine. The mean positional error was 0.40 m (Douglas-fir), 0.25 m (ponderosa pine), and 0.32 m (all trees).

beam). In addition, the echo from a lower resolution wide-beam pulse at the top of a tree crown will be a mixture of reflections from numerous different objects within the path of the laser beam (including the terminal leader and branches in the topmost whorl) and therefore will represent an integrated measurement rather than a discrete measurement of the highest point on the terminal leader (Baltsavias, 1999). Although the magnitude of the error at both beam sizes (approximately 0.5–1.0 m) indicates that lidar is rarely acquiring a precise measurement of the treetop location, the increased spatial resolution of narrow-beam lidar generally provides measurements that are closer to the true height of the tree crown apex.

The heights of ponderosa pines were measured more accurately than those of Douglas-fir, at both beam divergence settings. Systematic and random components of the tree height measurement error were significantly lower for ponderosa pine than for Douglas-fir (**Tables 3** and **4**). This difference in lidar error between pine and fir–spruce species types was more significant than that reported in other studies (Persson et al., 2002; Yu et al., 2004). This difference is most likely due to the differences in crown form between these species. The top of a Douglas-fir tree crown is much narrower than that of a pine, and it is much more likely to be completely missed (narrow beam) or return an insufficient signal to be detected (wide beam).

The horizontal errors in treetop detection were slightly greater at the narrow beam setting for both species (positional error of 0.50 m for narrow beam setting and 0.32 m for wide beam setting). This result would suggest that wide-beam lidar provides an integrated measurement of features at the crown apex that is generally centred on the treetop position, and narrow-beam lidar provides higher resolution measurements of individual branches near the treetop, which may be off-centre from the treetop location (especially in windy conditions). One must be cautious in drawing strong conclusions from these observations of horizontal error, however, since the nominal horizontal accuracy of the system is in the range of 50–55 cm and even a light wind can cause treetops to sway several decimetres.

In this study we were able to separate the influence of DTM error and treetop detection error in the measurement of tree height. The results indicate that, although the relative contribution of DTM error to the bias in tree height measurements is minor (0–10 cm, corresponding to 0%–10% of overall height error), in all cases DTM error contributed 10–20 cm to the variability in tree height measurements. It should be noted that these study areas were extremely flat and open — the influence of DTM error would be expected to increase in denser stands with more varied topography.

The measurements of tree height acquired with the Impulse hand-held laser rangefinder in the field were significantly more accurate than those acquired from lidar. Interestingly, most trees were underestimated with the Impulse. Although the cause of this is not entirely clear, there is often some systematic error in Impulse tree height measurements that is due to setting the true pivot point for measurement of vertical angles. Although care was taken to keep the pivot point constant, even raising the instrument a few centimetres (resulting in the pivot point moving back) could introduce several centimetres of bias in the measurement of height for a 40 m tree.

Conclusion

The emergence of lidar as a forest measurement tool promises to dramatically increase the efficiency of forest inventory programs. In numerous previous studies, tree height measurements acquired from high-density lidar have been shown to be highly correlated with tree heights measured in the field using conventional techniques. However, because all conventional field techniques introduce errors ranging from 1% to 10% in the measurement of tree heights, it was difficult to obtain a definitive statement of accuracy for lidar-derived tree height measurements. In this study, we developed a methodology for obtaining extremely accurate measurements of tree heights in the field and quantifying the accuracy of every measurement, drawing from the theory of least-squares adjustment in surveying engineering. These measurements were acquired with negligible error (~2 cm, or 0.05% in the case of a 40 m tree) and allowed for rigorous assessment of the influence of beam divergence, species type, and DTM error in the measurement of lidar tree height measurements for two of the most important species in western North America, namely Douglas-fir and ponderosa pine. Lidar height measurements acquired with narrow-beam lidar will be more accurate for both pine and Douglas-fir, and measurements of pine will be significantly more accurate than those for Douglas-fir. In addition, we were able to make a definitive statement regarding the accuracy of lidar measurements compared with conventional field techniques. Although the results indicated that field methods will yield more accurate tree height measurements than lidar, the reduced cost and increased efficiency of lidar survey will no doubt offset the slight difference in accuracy. In addition, it is expected that a species-specific correction factor could be applied to the lidar-derived measurements to reduce the influence of systematic error, and a better understanding of the random errors in lidar-derived tree height estimates can lead to a more explicit, and accurate, treatment of measurement error in the design of lidar-based forest surveys.

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