

Accuracy of a high-resolution lidar terrain model under a conifer forest canopy

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Abstract. Airborne laser scanning systems (commonly referred to as light detection and ranging or lidar systems) can provide terrain elevation data for open areas with a vertical accuracy of 15 cm. Accuracy in heavily forested areas has not been thoroughly tested. In this study, a high-resolution digital terrain model (DTM) was produced from high-density lidar data. Vegetation in the 500-ha mountainous study area varied from bare ground to dense 70-year-old conifer forest. Conventional ground survey methods were used to collect coordinates and near-ground vegetation heights at 347 ground checkpoints distributed under a range of canopy covers. These points were used to check the DTM accuracy. The mean DTM error was 0.22 ± 0.24 m (mean \pm SD). DTM elevation errors for four tree canopy cover classes were: clearcut 0.16 ± 0.23 m, heavily thinned 0.18 ± 0.14 m, lightly thinned 0.18 ± 0.18 m, and uncut 0.31 ± 0.29 m. These DTM errors show a slight increase with canopy density but the differences are strikingly small. In general, the lidar DTM was found to be extremely accurate and potentially very useful in forestry.

Résumé. Les systèmes laser à balayage aéroportés (communément appelés systèmes de détection et de télémétrie par la lumière ou systèmes lidar) peuvent fournir des données d'élévation de terrain pour les zones ouvertes avec une précision verticale de 15 cm. Leur précision dans les zones forestières denses n'a jusqu'à maintenant pas été testée en profondeur. Dans cette étude, un modèle numérique de terrain (MNT) à haute résolution a été produit à partir de données lidar haute densité. La végétation dans la zone d'étude de 500 ha située en zone montagneuse variait du sol nu à une forêt de conifères de 70 ans d'âge. Des méthodes conventionnelles de levés de terrain ont été utilisées pour collecter les coordonnées et les hauteurs de la végétation près du sol pour 347 points de contrôle au sol répartis selon une variété de couvert végétal. Ces points ont été utilisés pour vérifier la précision du MNT. L'erreur moyenne du MNT était de $0,22 \pm 0,24$ m (moyenne \pm ET). Les erreurs d'élévation du MNT pour quatre classes de couvert forestier étaient de : coupe à blanc $0,16 \pm 0,23$ m, fortement élaguée $0,18 \pm 0,14$ m, légèrement élaguée $0,18 \pm 0,18$ m et non coupée $0,31 \pm 0,29$ m. Ces erreurs du MNT indiquent un léger accroissement en fonction de la densité du couvert mais ces différences sont étonnamment faibles. En général, le MNT lidar s'est avéré très précis et le modèle présente un potentiel utile pour la foresterie.

[Traduit par la Rédaction]

Introduction

Airborne laser mapping is a remote sensing technology that is increasingly being used to map forested terrain. This mapping technology utilizes a laser light detection and ranging (lidar) system and an airborne navigation system that accurately tracks platform location and attitude to produce a dense array of geographic coordinates from points where laser pulses are reflected off a surface (Baltasvias, 1999). Over open areas with flat hard surfaces, lidar systems often achieve coordinate accuracies of 15 cm (Pereira and Janssen, 1999). However, over rough surfaces obscured by dense canopy and the understory of a conifer forest, the accuracy is compromised by uncertainty about the reflection point (i.e., whether it is from vegetation or from the ground surface). In such situations, accuracy of the lidar ground surface is influenced strongly by the ability to filter and sort the coordinate data into ground and off-ground classes so that the surface can be described by ground reflections only (Haugerud and Harding, 2001).

The accuracy of lidar surface mapping in a forest environment has not been thoroughly examined. Kraus and Pfeifer (1998) studied the Optech² ALTM 1020 laser scanner for mapping a wooded area (91 km²) in Austria. They report a vertical root mean square error (RMSE) of 0.57 m. However,

they do not provide information on the tree cover in the study area or mention the cover density near the ground checkpoints.

This study presents a more comprehensive investigation of the influence of forest parameters on the lidar-derived digital terrain model (DTM). We report the accuracy of this DTM in a variety of conifer canopy and near-ground vegetation conditions and describe how DTM accuracy varies with these conditions.

Approach

A small footprint, discrete return lidar system was used to map 5 km² of heavily forested lands in western Washington

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State. The site is mountainous with elevations varying from 150 to 400 m and ground slopes from 0° to 45°. **Figure 1** shows a 1999 orthophotograph of the study area taken 4 months before the lidar flight.

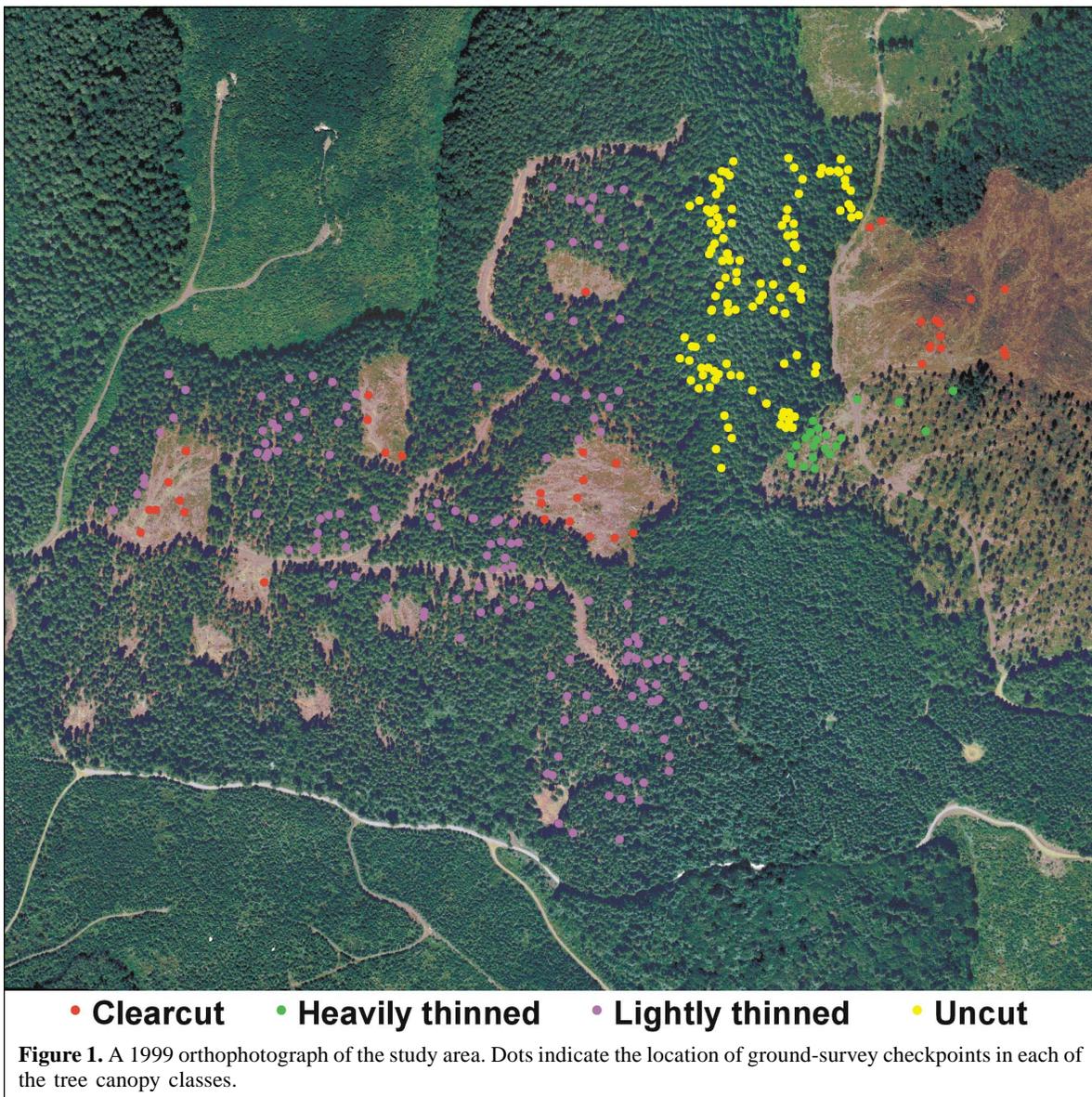
Forest canopy within the study area is primarily coniferous and highly variable. It includes recent clearcuts, areas thinned to varying tree densities, and forest plantations ranging from recently planted to 70-year-old mature forests. As part of a forest management study, the canopy of the 70-year-old forest stand was partially harvested in 1998, resulting in four different residual canopy density classes. In clearcut areas, the number of residual trees per hectare (TPH) is zero; in heavily thinned areas, approximately 40 TPH remain; in lightly thinned areas, 175 TPH remain; and in the uncut area, 280 TPH remain. The dominant tree height in the harvest area was approximately 50 m. **Figure 2** offers terrestrial views typical of the four forest densities found in the study area.

Lidar system

For this study, a Saab TopEye lidar system mounted on a helicopter was used to collect data over the study site in the spring of 1999. Flight parameters and instrument settings for the data acquisition are presented in **Table 1**.

Ground-surface DTMs

For this study, the contractor supplied the raw lidar data consisting of XYZ coordinates, off-nadir angle, and intensity for up to 4 returns/pulse. There were approximately 37 million points over the project area. The contractor sorted the data into “last returns” — approximately 6.5 million ground-point candidates in a rectangular, 5 km² area clipped out of the larger area. **Figure 3** shows a representation of a digital surface model (DSM) created using the last returns. As can be seen, some vegetation-related effects remain in the last-return data. The contractor, using a proprietary routine (most probably based



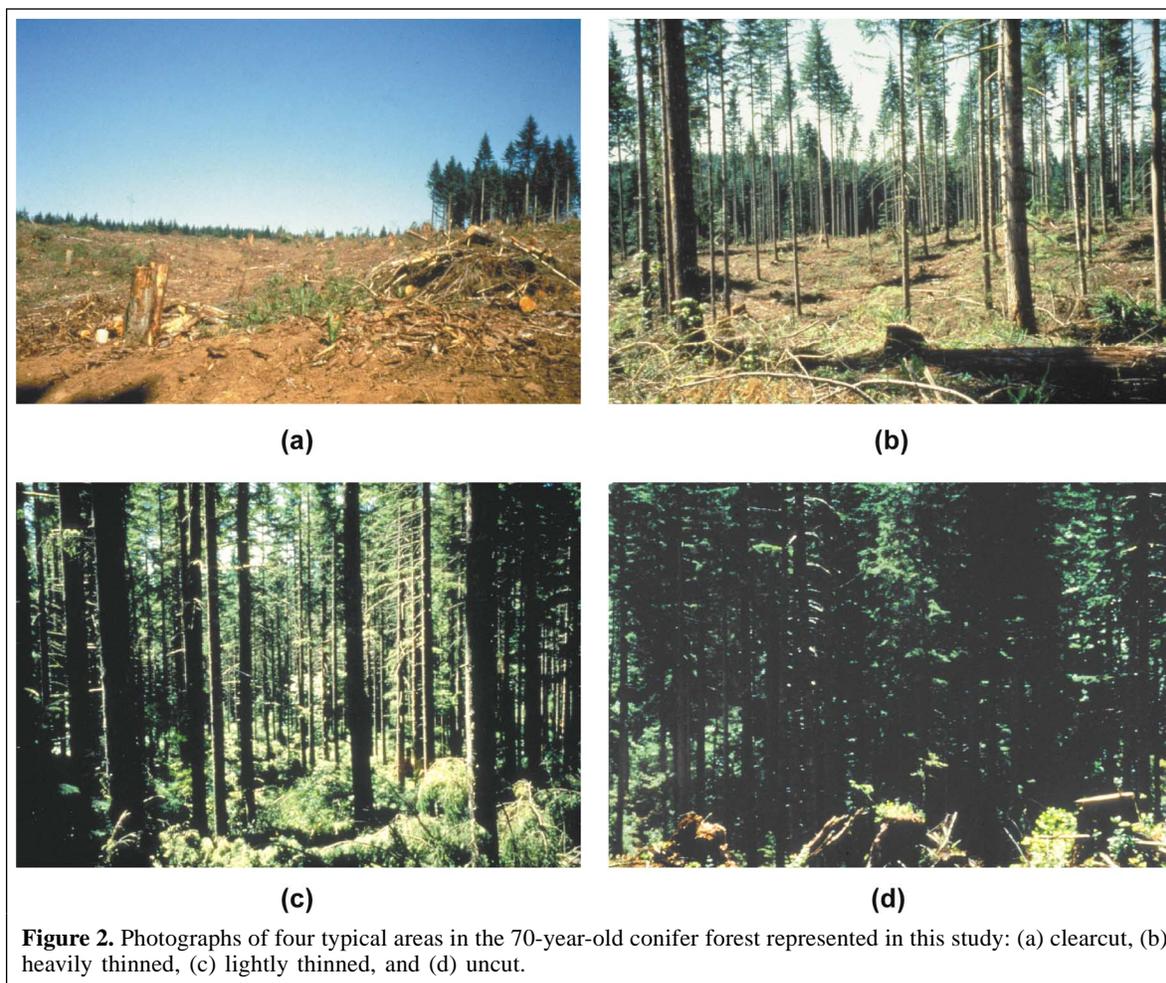


Figure 2. Photographs of four typical areas in the 70-year-old conifer forest represented in this study: (a) clearcut, (b) heavily thinned, (c) lightly thinned, and (d) uncut.

Table 1. Flight parameters and scanning system settings.

Flying height	200 m
Flying speed	25 m/s
Scanning swath width	70 m
Forward tilt	8°
Laser pulse density	4 pulses/m ²
Laser pulse rate	7000 points/s
Max. returns per pulse	4
Footprint diameter	40 cm

upon the removal of spikes), filtered the data further, down to approximately 4 million points taken to be on the ground. These filtered ground points were used as the source for the ground-surface DTM in this study.³

The filtered data were gridded using the inverse distance (squared) method (Golden Software, Inc., 1999) to produce a DTM with 1.52 m × 1.52 m spacing on the North American Datum 1983, State Plane Coordinate System (Washington

South Zone), with elevations in the North American Vertical Datum 1988. **Figure 4** shows a representation of this DTM. This DTM was used to determine elevation, slope, and slope aspect for all points in the study area.

Lidar data cylinders around checkpoints

In the following sections, the influence of forest parameters on the accuracy of the lidar-based DTM is expressed in several ways. To investigate the effect of local vegetation and terrain characteristics on DTM accuracy, the analysis was based upon cylindrical subsets of the data centered on each specific checkpoint. The checkpoints were located under the various canopy densities and surveyed on the ground. The cylindrical subsets were extracted from the complete raw lidar collection (**Figure 5**). In this study all raw lidar points within 3.81 m of a vertical axis passing through the ground checkpoint became the data set for that particular checkpoint.

³The final filtering of last returns for the purpose of generating “ground-surface” coordinate data is a commercially important and, therefore, inherently proprietary activity. Some discussions have been published in the open literature (Elmqvist, 2002; Haugerud and Harding, 2001); however, it is common practice for the consumers of lidar data to order the “ground-surface” coordinate data and accept it as a commercial product. In this study, we have worked with the filtered last-return, “ground-surface” coordinate data set as it was delivered.

Lidar DTM accuracy assessment

Lidar data would be most useful in the forestry context if one could expect that an accurate, high-resolution ground-surface DTM could be generated from the filtered last returns. Ideally, the accuracy would be uniform and not vary significantly with canopy, near-ground cover, or terrain relief. However, intuition suggests that these site conditions could have a significant effect on DTM accuracy. This investigation is designed to assess the magnitude of these vegetation and terrain effects.

Ground-surveyed checkpoints

We chose to check the DTM at ground-surveyed checkpoints distributed across the range of our forest canopy and near-ground vegetation cover conditions. A Topcon ITS-1 total station surveying instrument was used to survey 347 checkpoint locations in the central portion of the area (**Figure 1**). Approximately 85% of the survey points were under forest canopy. At each checkpoint, the survey crew measured the height of the vegetation (up to 6 m). For the purposes of this

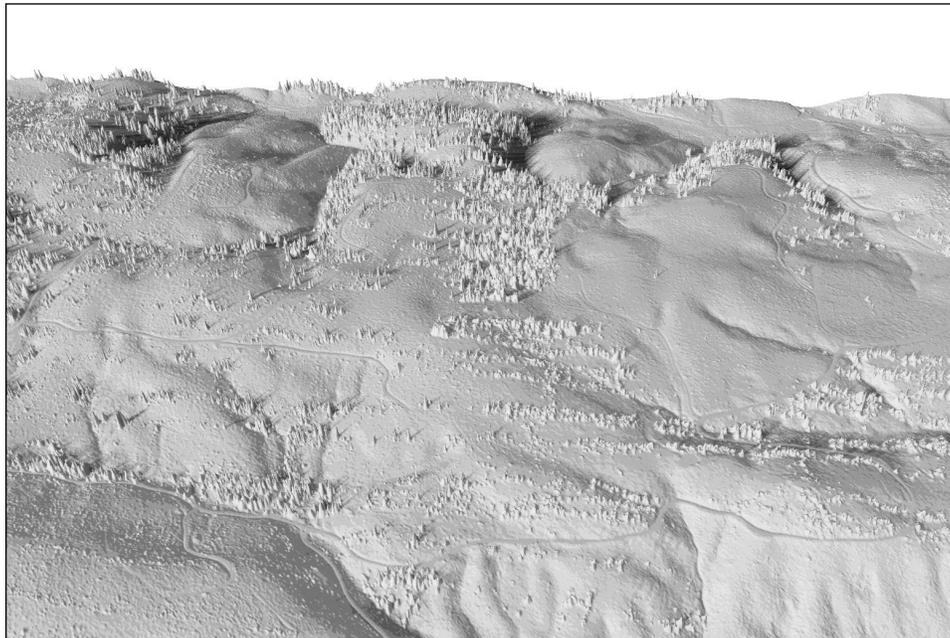


Figure 3. Shaded relief of the DSM formed from all the “last-return” lidar coordinate data.

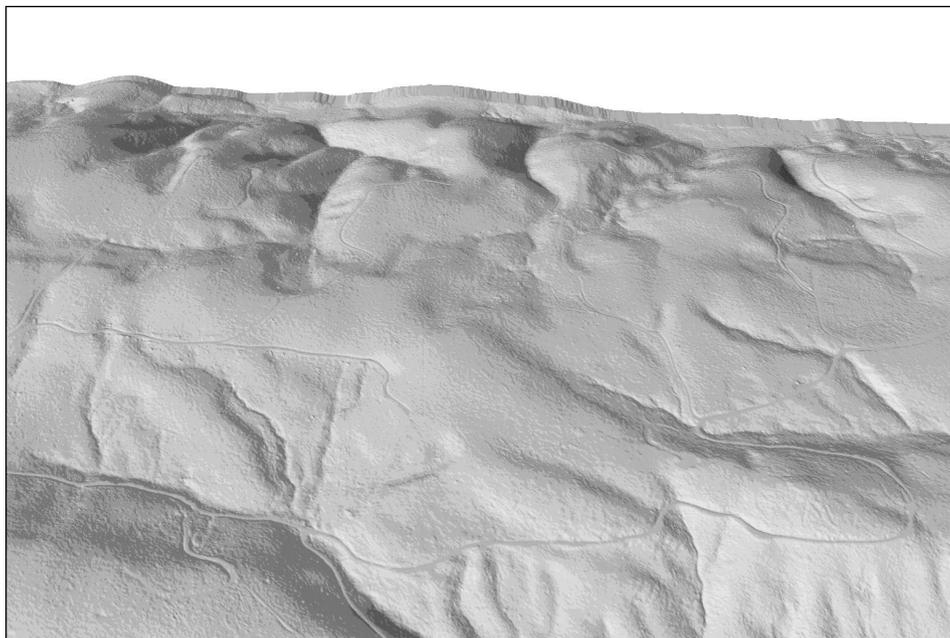
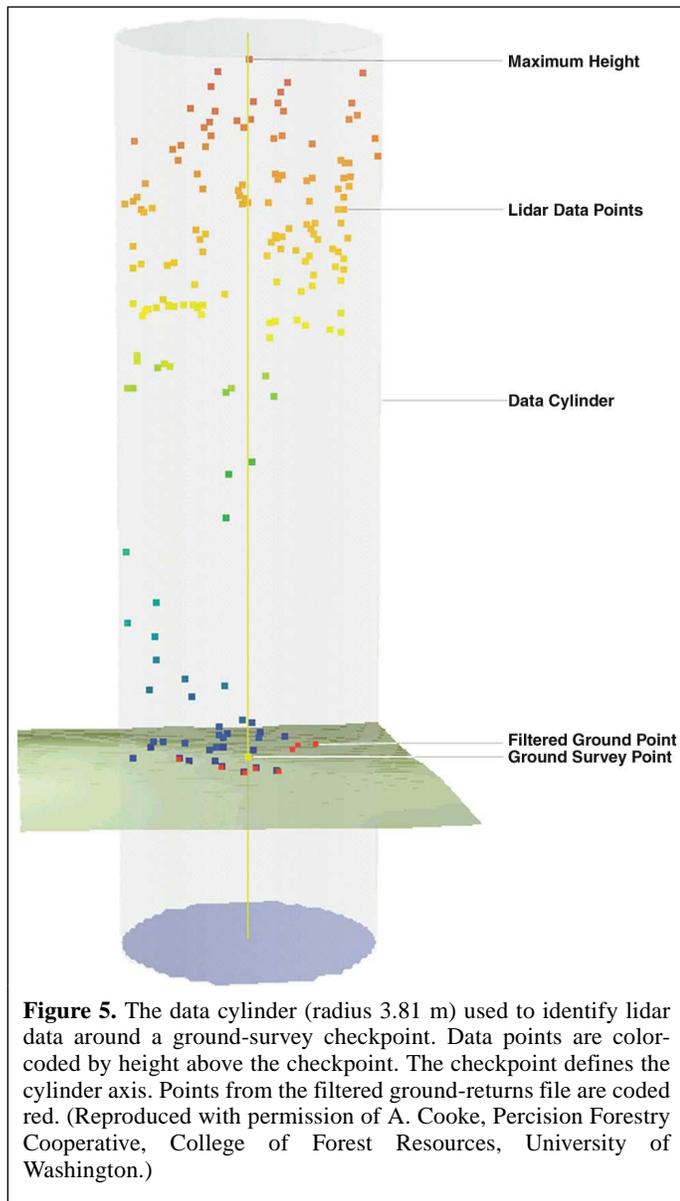
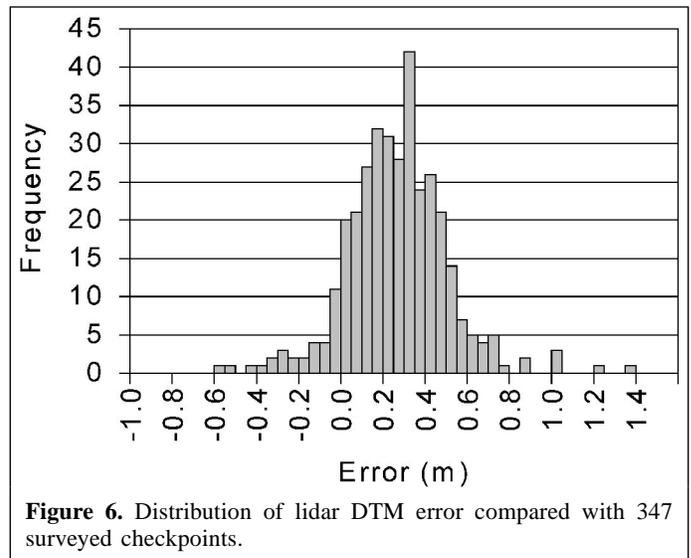


Figure 4. Shaded relief of the DTM formed from the lidar coordinate data filtered to distinguish “ground-surface” points only.



study, “near-ground” denotes vegetation directly above the checkpoint, up to a height of 6 m, and “understory” denotes vegetation directly above the checkpoint, with a height between 2 and 6 m. The ground survey consisted of three closed traverses that originated at reference points that had been established using survey-grade GPS. After adjustment of each traverse, the horizontal and vertical accuracies of ground points were approximately 15 cm and 3 cm, respectively.

The elevation of each checkpoint was compared with the elevation of the same horizontal position within the DTM. Because the DTM is a gridded model of the terrain surface, a bilinear interpolation was applied to compute the DTM elevation at the horizontal position of each survey checkpoint. The DTM elevation of the checkpoint was computed by interpolating between the four corners of the grid cell in which it was contained (Lemkow, 1977). **Figure 6** shows a frequency



distribution of the differences between the lidar DTM and the checkpoints.

The mean of the elevation differences between the lidar DTM and the 347 checkpoints was 0.22 ± 0.24 m (mean \pm SD). The range of the elevation differences was -0.63 to 1.31 m. Considering that the lidar DTM, even at the $1.52 \text{ m} \times 1.52 \text{ m}$ grid size, will necessarily miss the micro-topography of a forest floor that is roughened by downed logs and other features, this is a remarkable accuracy and considerably better than can be expected from traditional photogrammetric methods (Reutebuch et al., 2000).

Effect of tree canopy density on lidar DTM accuracy

A total of 108 tree inventory plots were established throughout the area to estimate the number of trees that were present in each portion of the study area. The ground checkpoints were then subdivided into four tree canopy density classes based on the number of trees per hectare (TPH) that were present in each area (**Figures 1** and **2**). Most of the dominant trees remaining in the study area where ground checkpoints were measured were of similar size and type. Some of the checkpoints that occurred on canopy class boundaries were eliminated, reducing the total to 326 checkpoints distributed into the four classes. Mean elevation differences and standard deviations between the ground checkpoints in each canopy class and the lidar DTM are shown in **Table 2**.

As expected, the magnitude of the lidar DTM error was greatest in the area under the uncut canopy, and the size of the means generally trends with the gross canopy density classes. The other variables, such as local canopy density, near-ground vegetation, and slope, were investigated separately.

Table 2. Differences, lidar DTM elevations minus surveyed checkpoint elevations, segregated by tree canopy class.

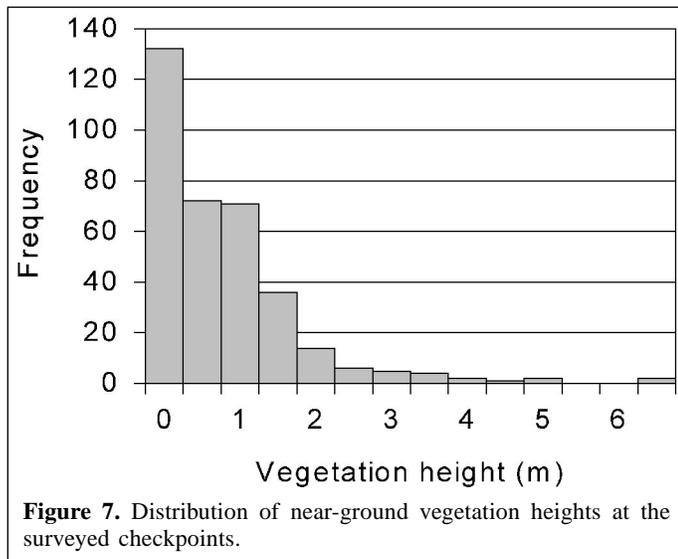
Canopy class	Mean (m)	SD (m)	Min. (m)	Max. (m)	No. of checkpoints
Clearcut	0.16	0.23	-0.48	0.61	38
Heavy thinned	0.18	0.14	-0.11	0.41	21
Lightly thinned	0.18	0.18	-0.63	0.69	147
Uncut	0.31	0.29	-0.60	1.31	120

Effects of grid spacing, local canopy cover, canopy height, near-ground vegetation, and slope on accuracy

Commercial lidar systems, operated over open areas with flat hard surfaces, are expected to achieve coordinate accuracies of ± 0.15 m (Pereira and Janssen, 1999). It is, therefore, somewhat surprising to find in a rough, forested environment with sections of full canopy and dense near-ground vegetation such as that sampled in our data (Figure 7) that a subset (~4 million points) of the total lidar dataset (~37 million points) can develop DTM elevations with accuracies such as those reported in Table 2.

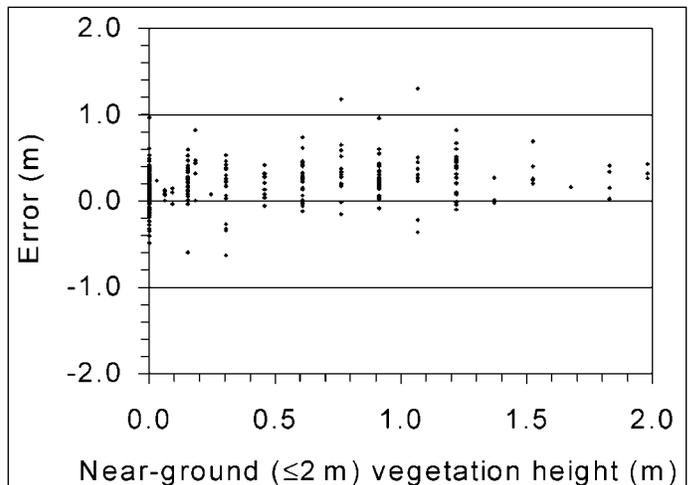
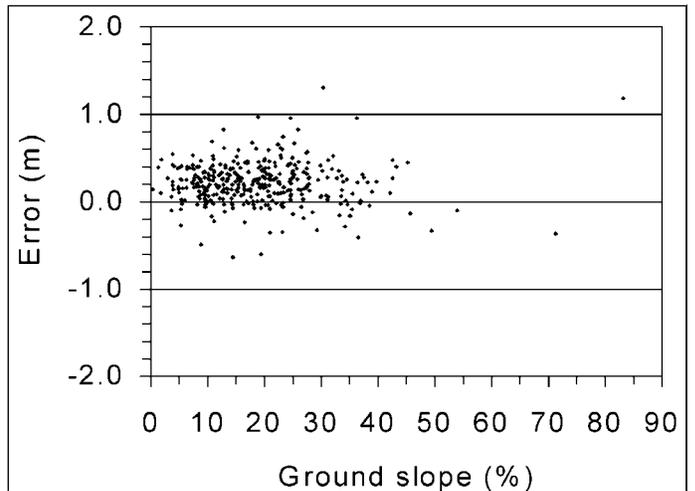
The residual error between each of the ~4 million filtered ground returns and the DTM was computed using a bilinear interpolation within grid elements (Lemkow, 1977). The mean DTM grid error is 0.00 m and the standard deviation is 0.22 m. The observed error in the clearcut area (0.16 m) is very similar to the lidar manufacturer’s stated accuracy of ± 0.15 m (Baltsavias, 1999). If one assumes that this error in the open, bare-ground clearcut area is the system bias and adjusts the individual checkpoint errors to remove this bias, then 69% of the observed checkpoint errors are within ± 0.22 m (the observed SD of the DTM grid error). Clearly, these small error magnitudes frustrate any attempt to develop significant correlations among the chosen variables. Therefore, the results are presented here in a descriptive form.

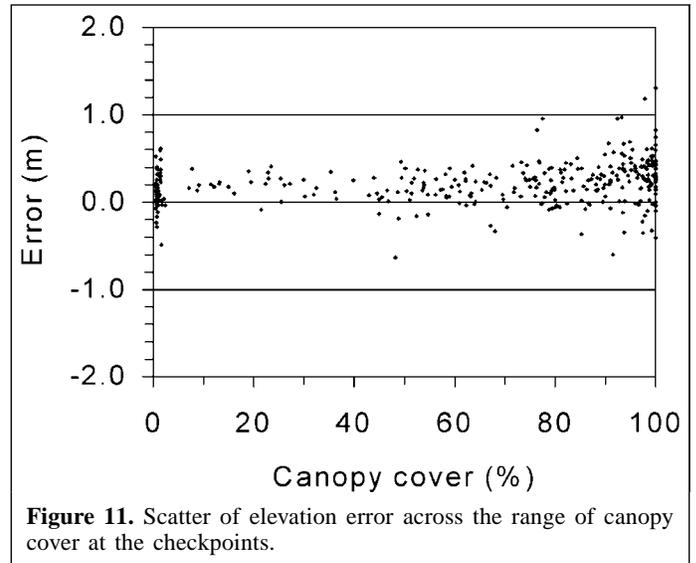
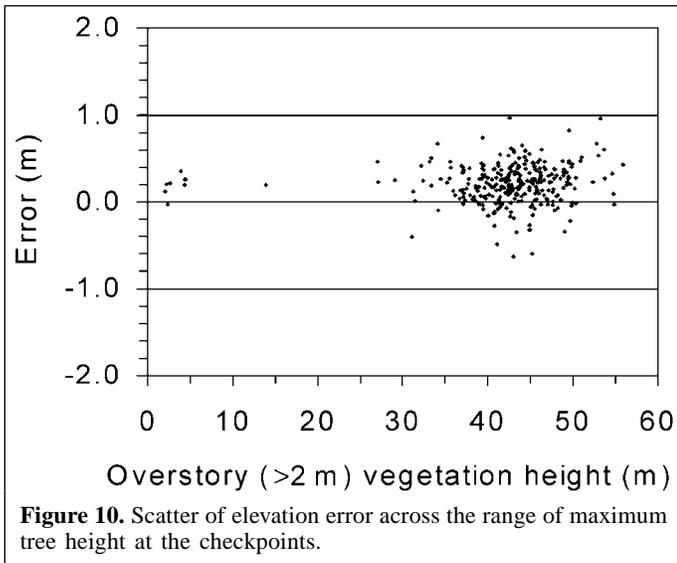
Figure 8 presents the errors in all 347 surveyed checkpoints plotted against the local slope as determined from the lidar



DTM. These are point-specific slopes; however, they would not strictly define the actual micro-topography since the DTM would cause some smoothing over its 1.52 m \times 1.52 m grid. Nevertheless, the slopes do vary from 0 to 83% with a mean of 19% and a median of 18%. Figure 9 presents the same elevation difference errors plotted against the near-ground vegetation height. Only the points where bare ground was noted (114 points clustered along the vertical axis at zero height) and the points with vegetation up to 2 m (another 192 points with vegetation heights between 0 and 2 m) are shown. The points with vegetation at heights recorded above 2 m and below 6 m (21 points classified in this study as “understory vegetation”) are not included in Figure 9.

Both Figures 10 and 11 display data that are derived from the “above-ground” lidar data selected by each 3.81-m radius data cylinder. Figure 10 displays the error data against the canopy height, defined as the maximum lidar height found inside the associated cylinder. This measure provides a rough





estimate of canopy height within the area of the survey point (Means et al., 2000).

The canopy cover percentages shown in **Figure 11** are derived from the cylinders of data as well. This lidar-based definition of canopy cover is taken also from the work of Means et al. (2000). The percentage canopy coverage is determined as the ratio of those first returns that are greater than 2 m above the ground divided by the total of the first returns in the data cylinder.

Near-ground and understory vegetation error groups

Because the error scatter plots display no obvious correlations among the variables of slope, near-ground vegetation, canopy height, and canopy cover (**Table 3**), the following data groupings are distinguished for analysis:

- All points — data associated with the entire set of 347 surveyed checkpoints.
- Group 1 — data associated with the surveyed checkpoints where near-ground vegetation heights were recorded as zero: in other words, points where the actual ground surface was devoid of vegetation, regardless of the overstory tree canopy condition above 6 m.
- Group 2 — data associated with all checkpoints that had vegetation within 6 m of the ground, regardless of the overstory tree canopy condition.
- Group 3 — data associated with only those checkpoints where near-ground vegetation is present and where near-ground vegetation height is less than 2 m.
- Group 4 — data associated with all checkpoints that have ground slope less than 18%.
- Group 5 — data associated with all checkpoints that have ground slope greater than or equal to 18%.

Table 3. The basic DTM-elevation minus surveyed-elevation error statistics for particular data groups.

Data group	Mean (m)	SD (m)	Min. (m)	Max. (m)	No. of points
All data	0.22	0.24	-0.63	1.31	347
Group 1	0.15	0.20	-0.48	0.97	132
Group 2	0.26	0.25	-0.63	1.31	212
Group 3	0.25	0.25	-0.63	1.31	193
Group 4	0.21	0.20	-0.63	0.83	174
Group 5	0.22	0.28	-0.60	1.31	173

Discussion

Overall, the lidar DTM appears to be remarkably accurate given the thick forest canopy, the presence of dense and often high near-ground vegetation, and the rugged terrain in the study area. The mean and standard deviation of vertical error between the DTM and 347 ground checkpoints are 0.22 m and 0.24 m, respectively (RMSE = 0.32 m). This error is similar but lower than that obtained by Kraus and Pfeifer (1998) for a wooded area in Austria (RMSE = 0.57 m). In their study, a fixed-wing aircraft was employed, resulting in an average point spacing of 3 m. Kraus and Pfeifer chose to produce a gridded 3 m × 3 m DTM from their data. In our study, the lidar sensor was flown on a slow-moving helicopter. The density of raw lidar data within our 7.62 m diameter data cylinders averaged 4.22 points/m²: a point separation closer to 0.5 m.

The 1.52 m × 1.52 m gridded DTM used in this study was based only upon the filtered ground returns. There was an average of 26.36 filtered ground-return points per data cylinder or 0.58 points/m²: a separation of approximately 1.3 m. However, the number of ground returns varied widely: a standard deviation of 23 points per data cylinder across our 347 surveyed points with nearly 5% having no ground returns and 20% having fewer than seven within their respective data

cylinders. Such wide variations in spacing were expected because of tall trees, heavy canopy, near-ground vegetation, and rugged terrain. It was because of these conditions that we chose initially to fly high-density lidar coverage to insure sufficient numbers of ground returns throughout the area. The high density does seem important if one hopes to characterize the micro-topography under a dense forest.

Still, one expects that both the forest canopy cover and the near-ground vegetation height would affect the DTM accuracy and, indeed, the results show a small but significant effect. A two-sample Z-test of the difference between the error means for lightly thinned and uncut canopy classes showed a significant difference ($P < 0.001$). However, this difference between means (0.13 m) is extremely small and much less than might be expected, given the extremely dense overstory tree canopy of the uncut 70-year-old Douglas-fir area. Likewise, a two-sample Z-test of the difference between the error means for Group 1 (areas with no near-ground vegetation, regardless of overstory tree canopy condition) and Group 2 (areas with near-ground or understory vegetation, regardless of overstory tree canopy condition) showed a significant difference ($P < 0.001$). And again, this difference between the means (0.11 m) is extremely small and much less than might be expected, given the dense near-ground and understory vegetation encountered in the study area.

Aside from the errors expected from the laser scan being obstructed or diverted by vegetation, one would naturally expect some errors due to the important platform location and orientation recordings from the navigation system. Our raw lidar data came from 12 passes over the test area and most of the 7.62-m diameter cylinders centered on surveyed checkpoints included data from several (an average of 2.5 and up to 4) of these passes. The DTM was derived, of course, from the data of all passes. As a check for questionable, pass-related data, the DTM elevation minus data elevation means were computed for each pass. The means were not large; they ranged between 0.08 and 0.31 m. We were not able to attribute this pass-related variation to our forest characteristics, nor to other lidar system-related characteristics such as the angles of the scan geometry. It does appear that the between-pass system errors are of the same magnitude as the errors induced by canopy or vegetation.

Finally, it should be mentioned just how great an advance this lidar technology offers for the precision and accuracy of DTMs over forested land. Currently, all areas in the Pacific Northwest of the U.S. are provided DTMs by the United States Geological Survey (USGS) with resolutions of both 30 m \times 30 m and 10 m \times 10 m grids. These DTMs originated either from aerial photographs and photogrammetry or directly from a conversion of the contour lines existing on the 1:24 000 USGS map series. Carson and Reutebuch (1997) rigorously tested the accuracy of these DTMs over a sample set of 23 large forested areas — 13 in areas of dense canopy (westside of Cascade Mountain range) and 10 in areas of light canopy (eastside). The elevation errors were determined at thousands of points to a precision of 1 m. The westside samples showed min, max

ranges of -59 to 45 m with a RSME of 9 m. The eastside ranges were -25 to 22 m with a RSME of 5 m. Clearly, the RMSE of 0.32 m found in this study offers at least one order of magnitude improvement in accuracy over the available DTMs.

Conclusions

In this study it was determined that a lidar-based, ground DTM over mature forested areas can be extremely accurate. The high-density lidar provides enough reflections from the ground — approximately 1 return/m² in this study — to generate a DTM that can precisely model the micro-topography of a typical conifer forest. The accuracy is eroded slightly by heavy canopy and the height of near-ground vegetation, but the effect is weak. In fact, if sub-meter accuracy is the goal, it seems that the system navigational errors are likely to form the largest contribution to the total overall error budget.

It was costly and laborious to conduct this accuracy test in a heavily vegetated, mountainous area. Not every circumstance will warrant an assessment based upon a closed traverse with a survey instrument. There is a great need for better methods to verify lidar data accuracy, particularly in forested areas where the GPS system does not function well.

Although we can conclude that high-density lidar is accurate enough to be of great benefit to forestry, the high cost is a concern. Even the relatively inexpensive photogrammetric mapping is often not justified today by many forestry operations. However, the potential for a DTM to locate small streams and gullies, high-risk erosion sites, and to provide for better road and harvest planning promises to justify a larger investment in mapping. Certainly, the potential of higher resolution lidar mapping should be investigated further.

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