THE EFFECT OF BIOMASS AND SCANNING ANGLE ON LASER BEAM TRANSMITTANCE

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ABSTRACT:

During the last decade, there have been numerous scientific studies verifying the accuracy of digital elevation models (DEM) derived from airborne laser scanning (ALS). Since ALS has increasingly been used for nationwide digital elevation model data acquisition, optimizing ALS acquisition parameters is a topic of interest to national land surveys. In particular, the effect of the scanning angle and biomass on elevation-model accuracy needs further study in heavily-forested areas. The elevation-model accuracy is affected by, for example, the number of pulses hitting the ground, footprint size, terrain slope and, especially, vegetation. In order to better understand the effect of the biomass and scanning angle on the penetration rate of ALS signal through canopy and give further support to ALS studies, especially for scanning angles beyond 15 degrees of the nadir point, we conducted an indoor experiment using small spruce trees to represent forest canopy. The indoor experiment allowed us to measure the biomass reference accurately. We used manual thinning to produce various levels of biomass and scissor lift as the carrying platform. We measured the weight of every tree and the total biomass of trees after each thinning phase. We removed the material homogeneously from the trees, starting from the latest shoots. We used a FARO laser scanner in the experiment and attached it to the scissor lift. We scanned the experimental plot from four altitudes (about 3, 5, 7 and 9 m) and at six biomass levels (about 0, 6, 9, 14, 20 and 25 kg). The results show that signal transmittance through spruce trees is a function of biomass and scanning angle, but that the scanning angle only has a minor effect on the results. Biomass is the major parameter in determining the quality of the elevation model. While the results require further airborne experiments to be fully confirmed, they do imply that a scanning angle greater than 15 degrees can be applied in regions having low and moderate biomass, and due to the significant effect of the biomass on the transmittance, the airborne scanning missions must be carefully specified in heavily-forested terrain. We also found that terrestrial laser scanning experiments performed in an indoor laboratory-type setting yielded a relatively good understanding of the basic behaviour of and interaction between the target and laser scanning rather easily, but that it will be considerably more difficult to obtain similar results in a real-life experiment due to limited accuracy when collecting the reference data.

1. INTRODUCTION

Airborne laser scanning has been used for topographic mapping and forestry applications for many years. The accuracy of Digital Elevation Models obtained over forested areas has been described by, for example, Kraus and Pfeifer (1998), Hyyppä et al. 2001), Ahokas et al. (2002), Reutebuch et al. (2003), Takeda (2004), Sithole and Vosselman (2004), Hyyppä et al. (2005), Su et al. (2006), Chasmer et al. (2006), and Morsdorf et al. (2008). A detailed comparison of the filtering techniques used for DEM extraction was made within an ISPRS comparison of filters (Sithole and Vosselman 2004). Reutebuch et al. (2003) reported random errors of 14 cm for clear-cuts, 14 cm for heavily-thinned forest, 18 cm for lightly-thinned forest and 29 cm for uncut forest, using TopEye data with 4 pulses per m^2. The variation in ALS-derived DEM quality with respect to date, flight altitude, pulse mode, terrain slope, forest cover and within-plot variation was reported by Hyyppä et al. (2005).
Ahokas et al. (2005) proposed that the optimization of the scanning angle (i.e. field of view) is an important part of nationwide laser scanning. Significant savings can be realized by increasing the scanning angle and flight altitude. The initial results obtained using scanning angle analysis showed that the scanning angle had an effect on the accuracy of Digital Elevation Models, but that other factors, such as forest density, dominate the process. Scanning angles up to 15 degrees seem to be usable for high-altitude laser scanning in the boreal forest zone. High-altitude laser scanning yielded a precision measurement of about ±20 cm (std), which is good enough for most terrain models required in forested areas. Ahokas et al. (2005) stressed that the effects of the scanning angle should be studied further, since the maximum field of view for commercial laser scanners can be up to 75 degrees.
Su et al. (2006) analyzed the influence of vegetation, slope and the LiDAR sampling angle (the laser beam angle from nadir) on DEM accuracy. Vegetation caused the greatest source of error in the LiDAR-derived elevation model. It was also reported that DEM accuracy decreased when the slope gradient increased. Off-nadir scanning angles should be less than 15 degrees to minimize the errors coming from high slope gradients. The LiDAR sampling angle had little impact on the measured error. Chasmer et al. (2006) investigated laser pulse penetration through a conifer canopy by integrating airborne and terrestrial LiDAR. They found that pulses with higher energy penetrate further into the canopy. The authors suggest that future research should concentrate on improving the understanding of how laser-pulse returns are triggered within vegetated environments and how canopy properties influence the location of the trigger event. Morsdorf et al. (2008) assessed the influence of flying altitude and scanning angle on biophysical vegetation products (tree height, crown width, fractional cover and leaf area index) derived from airborne laser scanning. Due to the small scanning angle of the TopoSys Falcon II (±7.15 degrees), the dependence of airborne laser scanning on the incidence angle is not so evident. The incidence angle (angle to surface normal of the horizontal plane) seems to be of greater importance for vegetation density parameters than the local incidence angle (the angle to surface normal in the elevation model). The local

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topography is thus less important than the scanning angle. ALS data from larger scanning angles should be used to study further the effect of scanning angle on vegetation density products.
In order to separate the effects of vegetation and the scanning angle on the accuracy of the elevation model, especially beyond 15 degrees of the nadir point (which has not yet been studied), we carried out an indoor experiment. The controlled indoor conditions eliminated the effect of slope from the possible sources of error present in terrain measurements. In this test, we took the number of laser beams that were emitted versus those that were recorded hitting the ground and compared them using various canopy densities and scanning angles. The basic assumption of the study was that the number of laser hits reaching the ground serves as the main source affecting elevation model quality. Thus, we studied the transmittance through the canopy as the function of biomass and scanning angle. The laser beam size and triggering algorithm that we applied differs from system to system and from terrestrial to airborne systems, and, thus, the final results need to be verified in future airborne tests.

2. MEASUREMENTS

2.1 Terrestrial laser scanning

The applied terrestrial laser scanner (TLS) was a FARO Photon 80, which is based on phase measurements that provide high-speed data acquisition. The technical parameters of the scanner include a maximum measurement rate of 120,000 points/s, a wavelength of 785 nm, a vertical field of view of 320 degrees and a horizontal field of view of 360 degrees, and a ±2 mm systematic distance error at 25 m. A beam divergence is 0.16 mrad and a beam diameter at exit is 3.3 mm (circular) (www.faro.com). The resolution setting that we used was 1/8 of the full scanning resolution, which is to say 13.9 points/degree or 0.072 degrees/point. The resolution is the same for the vertical and horizontal directions. The phase-shift-based system uses an amplitude-modulated laser beam. The phase shift between the transmitted and the received signal is measured. Ambiguity can be resolved by using the multi-wavelength phase shifts (RP Photonics 2010, Kikuta et al. 1986). If the continuous, multi-wavelength amplitude-modulated beam hits multiple targets, the measurement range is not well-defined. The ALS is typically a pulse-based system which gives multiple returns. The phase-shift-based system can be used to approximate the penetration rate of the ALS pulse-based system, since ground return does not exist when several hits are encountered. Thus, the phase-shift-based system gives a lower bound (worst case scenario) for the penetration rate than the pulse-based system does. Since the triggering algorithm of each laser scanner is different, and is also affected by the laser beam size and the sensitivity of the receiver, the results need to be verified separately for airborne systems. The results can be used to better understand the effect of the scanning angle in relation to the biomass on elevation models.

For this study, we used a Genie GS3232 scissor lift, which has a maximum platform level of 9.8 m. We attached the FARO scanner to the front safety fence of the platform. The level and the function of the scanner were controlled from the lobby floor. Cf. Figures 1 and 2.

We scanned the experimental plot from four altitudes (about 3, 5, 7 and 9 m) and at six biomass phases (about 0, 6, 9, 14, 20 and 25 kg (Fig. 3)). The scanning angle is the angle between the nadir point under the laser scanner, the laser scanner and the point at which the laser beam hits the target. By changing the scanning height, it was possible to record a larger scale of scanning angles (from 6 to 38 degrees) over the test plot than by using only one scanning height. The scanning angle categories for 9, 7, 5 and 3 m heights were 6-15, 8-19, 11-26 and 17-38 degrees (Table 6).

Figure 1. Spruce trees and the FARO scanner in the lobby. Thinning phase th0. Photo M. Kurkela.

Figure 2. The FARO scanner at the 9 m high position. Photo J. Hyyppä.

2.2 Reference data

We placed the spruce trees (*Picea abies*) on a base (base height about 20 cm) on the floor of the Institute lobby at a point that was high enough for us to take measurements from different altitudes using a lift. We weighed every tree before commencing with the experiment. We extracted the biomass from the trees gradually by hand. We also weighed the thinned parts of the trees (mainly branches) after every thinning phase. We removed the latest shoots first, after which we removed the rest of the parts of the trees at an even rate. Figure 3 shows the decreasing amount of the total biomass. Our plan for cutting an equal amount of mass at every phase was quite successful, which is indicated by the almost linear curve for the diminishing biomass.

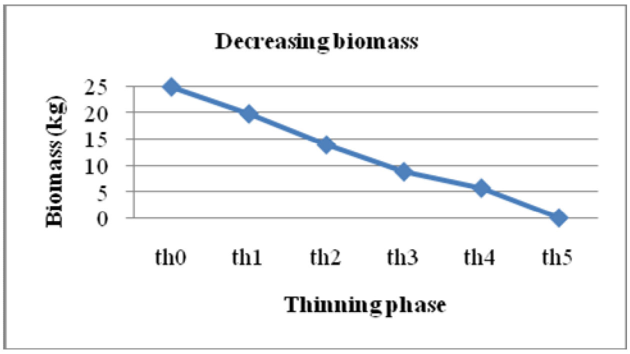

Figure 3. Spruce biomass decreasing during the experiment.

The thinning phases can be described as follows: Th0 indicates the untouched original biomass, when all the needles and branches were still on the trees (Fig. 1); during phases th1 and th2 some of the branches were removed (Fig. 4); during phase th3 only minor branches and the tree trunks remained; th4 indicates a clear-cut situation and the final phase, th5, indicates the cleaned plot area, when all the laser beams hit the ground without encountering any obstacles.

Figure 4. Thinning phase th2.

2.3 Analysis

For the statistical analysis, we used the two-factor analysis of variance. In the relevant literature, it is also called the complete block design (Montgomery 1984). With this analysis it is possible to find out whether the two factors differ from each other. Test statistic F is defined as

$$F = \frac{MS_{factor}}{MS_{err}}, \qquad (1)$$

where MS_{factor}=mean square of the factor
MS_{err}= mean square of the error

We compared test statistic F with the F distribution critical value $Fcrit_{\alpha,\upsilon1,\upsilon2}$ to determine its significance at the significance level of α=0.05. υ1 represents the degree of freedom of the factor and υ2 the degree of freedom of the error. If F>$Fcrit_{\alpha,\upsilon1,\upsilon2}$, then there are statistically significant differences within the factor. In this study, the biomass of the trees was the first factor and the scanning angle was the second factor. In Tables 7, 8, 10 and 12, P stands for the probability that the result for the significance was purely a coincidence.

We determined the laser points transmittance as a ratio of the ground points (H<20 cm above the floor) and the total number of points in the plot. Using this height limit, we considered the tree base points as ground points.
To study the effect of the scanning angle, we divided the entire view of interest at each scanning height into three parts. For example, we stratified scanning angles between 6 and 15

degrees at the 9 m scanning height into 6-8, 9-11 and 12-15 degree categories. In a similar manner, we stratified the observations from other scanning heights into three categories. The mean values of each scanning angle category are presented in Fig. 6 and 7. We examined the F statistics using all the scanning angle categories (12=4 heights x 3 categories) within the same scanning angle factor.

We analyzed the front edge of the test plot facing the scanner side separately. In this region, the spruce trees have fewer branches that prevent the laser beam from penetrating the canopy. We have studied the effects from this phase of the research by analysing the so-called front part angles separately.

3. RESULTS

Laser beams penetrate the original dense spruce stand poorly; (Figure 5 and Table 6) their rate of transmittance to the ground level is about 1-2%. After the thinning at phase th1, the transmittance rate was 5-6%. The next thinning phase increased the transmittance rate to 20-31%. The giant leap in the amount of transmittance after that is the result of leaf area loss when the branches are cut off.

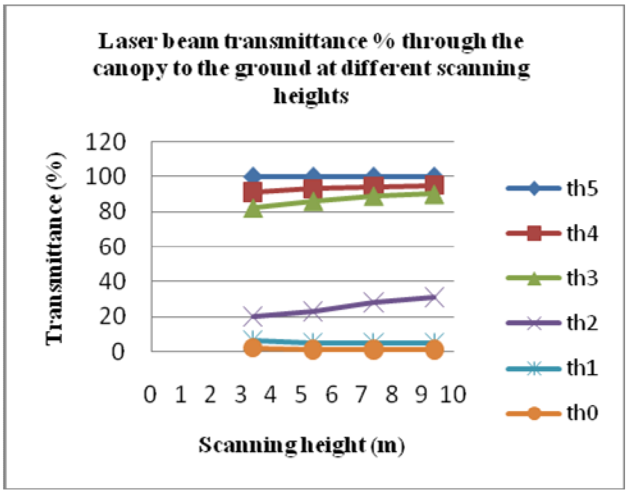

Figure 5. Transmittance through the canopy to the ground at different scanning heights and thinning phases.

Biomass (kg), thinning phase	T(%), 9 m, 6°-15°	T(%), 7 m, 8°-19°	T(%), 5 m, 11°-26°	T(%), 3 m, 17°-38°
24.84 (th0)	1	1	1	2
19.76 (th1)	5	5	5	6
13.88 (th2)	31	28	23	20
8.76 (th3)	90	89	86	82
5.68 (th4)	95	94	93	91
0 (th5)	100	100	100	100

Table 6. Transmittance T as a percentage of the laser beams reaching the ground from four altitudes. Minimum and maximum scanning angles in degrees.

When we treated each of the scanning heights as a single-angle category (data from Table 6), the biomass served as a significant factor in transmittance change at the α=0.05 significance level whereas the scanning angle did not (Table 7).

Factor	F	P	Fcrit	
Biomass	1635.55	5.73E-20	2.90	*
Scanning angle	2.79	0.08	3.29	

Table 7. F statistic for one scanning angle category per scanning height. Significance level α=0.05. *=factor statistically significant.

When we divided the scanning angles into three equal parts at each scanning height, the scanning angle factor contains a total of 12 angle categories to study instead of only 4, as in Table 7. Table 8 also shows that the scanning angle now becomes a significant factor affecting the rate of transmittance through the spruce canopy.
We also examined the three angle categories per each height separately. The F statistic is presented in Table 10.

Factor	F	P	Fcrit	
Biomass	668.43	6.43E-48	2.38	*
Scanning angle	4.76	4.2E-05	1.97	*

Table 8. F statistic for all scanning angles (12 categories). Significance level α=0.05. *=factor statistically significant.

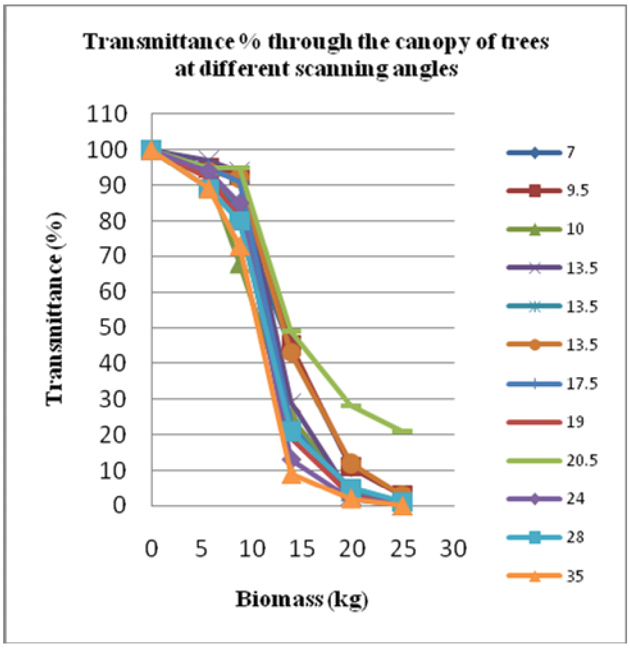

Figure 9. Transmittance through the canopy of trees at different scanning angles (from 7 to 35 degrees). We stratified the scanning angles into three parts at each height. The angle value presented is the mean value of each part.

Height (m)	Factor	F	P	Fcrit	
3	Biomass	95.08	4.24E-08	3.33	*
	Scanning angle	10.82	3.15E-03	4.10	*
5	Biomass	173.38	2.23E-09	3.33	*
	Scanning angle	3.63	0.07	4.10	
7	Biomass	249.01	3.73E-10	3.33	*
	Scanning angle	3.45	0.07	4.10	
9	Biomass	148.79	4.74E-09	3.33	*
	Scanning angle	2.34	0.15	4.10	

Table 10. F statistic for every scanning height when scanning angles were divided into three parts. Significance level α=0.05. *=factor statistically significant.

The scanning angle was only significant during observations at the scanning height of 3 m at the α=0.05 significance level. At that height, the variability in scanning angles was 17-38 degrees, making it significantly larger than at other heights. Furthermore, the biomass was a significant factor at all scanning heights.

The laser beam transmittances through the canopy and the scanning angles in front of the test plot facing the scanner are depicted in Figure 11. The scan (mean angle=20.5 degrees) taken at the height of 3 m differs from the other scans.

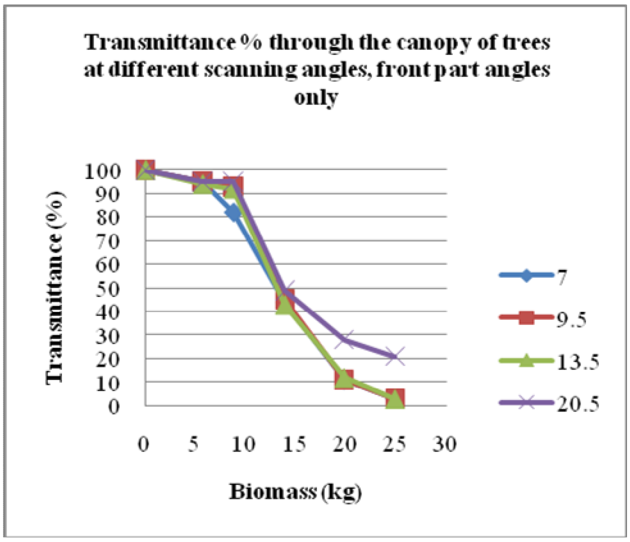

Figure 11. Transmittance through the canopy of trees at different scanning angles. Only the front part angles are presented for each scanning height (9, 7, 5 and 3 m).

If we omit the front part angles (with mean values of 7, 9.5, 13.5, and 20.5 degrees) from the scanning angle factor and examine the F statistics using all the remaining scanning angles in the angle factor, then the scanning angles are no longer statistically significant at the α=0.05 significance level. A significantly larger test plot would have helped to eliminate this effect caused by the front part angles.

Factor	F	P	Fcrit	
Biomass	990.39	1.23E-36	2.49	*
Scanning angle	2.11	0.07	2.29	

Table 12. F statistic when front part scanning angles were extracted. Significance level α=0.05. *=factor statistically significant.

4. DISCUSSION

The scanning angle had only a minor effect on the results compared to changes in the biomass. Dense canopy was the main source of transmittance deterioration as well as elevation-model accuracy deterioration. From the point of view of specifying ALS DEM quality, the results confirm the initial assumptions by Hyyppä et al. (2005) and Su et al. (2006) that the canopy is the main source for errors in the DEM accuracy. In order to be able to specify DEM quality, one has to know the properties of the forest canopy or be able to accurately specify the necessary accuracy for certain biomass or forest-condition levels. Thus, it is not feasible to specify acceptable rates for DEM accuracy without knowing the forest biomass.

In this study, we used a terrestrial laser scanner instead of an airborne scanner, since we needed to achieve an accurate reference. If there are multiple reflections from the target area, the distance given by the phase measurement method is not well-defined. Thus, this system exaggerates the effect of the scanning angle and diminishes the amount of ground-reflected points. Since the transmittance rate through the forest can be only a matter of a few percentage points, even a reasonable increase in the number of transmitted laser beams does not necessarily help in reaching acceptable DEM accuracy rates. We, therefore, believe that the results give valuable guidelines for pulse-based ALS, even though the beam size and different triggering algorithm varies from system to system, meaning that the results need to be verified through airborne experiments. Based on this experiment as well as prior research on forested conditions, we recommend using a number of pulses per square metre as a feasible criterion in specifying the laser scanning missions and making offers comparable rather than trying to obtain sufficient elevation model accuracy by specification, which requires a priori knowledge of forest conditions.

The authors believe that the most valuable contribution of this study is that it demonstrates how laboratory-type indoor terrestrial laser scanning experiments can be used to study the basic behaviour of the target and laser scanning interaction, which would be far too complicated to carry out via commercial ALS experiments. In this case, the number of sensors providing large scanning angles was limited (consisting only of Leica sensors), and it was very difficult to carry out enough accurate biomass measurements for all scan angles and biomass classes. Therefore, we urge researchers to conduct more laboratory-type studies in the future, which will provide better understanding of the basic interaction of laser beams with the target. Within the scientific community, acceptance of ALS has proceeded at a much faster rate than supporting research. Therefore, small laboratory-type experiments, such as the one depicted in this paper, can provide a quick and basic understanding of the phenomena with lower costs. The final conclusion can then be more easily confirmed using airborne experiments.

5. CONCLUSION

Results show that laser-beam transmittance through a small canopy of spruce trees is a non-linear function of biomass. The scanning angle has only a minor effect on the results compared to changes in the biomass. Scanning angles up to 38 degrees proved feasible for elevation mapping through this indoor experiment. Thus, airborne experiments which have a scanning angle greater than 15 degrees still need to be performed, especially in areas with low and moderate levels of biomass. Dense canopy was the main source of transmittance deterioration and, thus, of elevation model accuracy deterioration.

We showed by way of a light experiment that laboratory-type indoor terrestrial laser scanning experiments can be used to study the basic behaviour of and interaction between the target and laser scanning, which confirms previous results from airborne experiments and suggests new possibilities for extending the scanning angle for ALS surveys of areas with low and moderate levels of vegetation.

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