FACTORS AFFECTING THE QUALITY OF DTM GENERATION IN FORESTED AREAS

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ABSTRACT

Airborne laser scanning (ALS) has become an established tool for acquiring digital terrain models (DTM) in forested areas. Even though, there have been several empirical studies on DTM quality with laser scanning, a few studies have focused on factors affecting the quality of DTM generation. This paper analyses especially the effects of the date, flight altitude, pulse mode, terrain slope, forest cover and plot variation on the DTM accuracy at boreal forest zone. The boreal test site was collected with Toposys I and Toposys II in 1998, 2000 and 2003. Since the measurements were recorded at various time of the season, i.e. May 14th 2003 (leaf-off), June 14th 2000 (leaf-on, low development of undergrowth), and September 2nd 1998 (leaf-on, high undergrowth), it was possible to estimate the effect of leaves and undergrowth. In 2003 the flight altitudes of 400, 800 and 1500 m above ground level were used providing nominal pulse densities of 8-10, 4-5 and 2-3 pulses per m^2. At boreal forest zone, the random errors of less than 20 cm were obtained in most conditions for non-steep terrain. The increase of flight altitude 400 to 1500 m increased the random error of DTM derivation by 50%. The difference of using first or last pulse caused a similar random error difference. There were systematic shifts in the elevation models derived at various flight altitudes. It is expected that the beam size and sensitivity of the laser system determine this systematic behaviour. Additionally, the systematic shifts between last and first pulse were significant. The difference of DTMs derived at optimum and non-optimal season conditions were typically less than 5 cm for high-density data. In stands consisting of deciduous trees, the seasonal effects were the highest. The random error increased with increasing terrain slope. The effect of forest cover was higher when moving closer to the trunk. The results were site dependent, i.e. the obtained accuracy varied strongly as a function of site conditions.

1. INTRODUCTION

Airborne laser scanning (ALS) has become an established tool for acquiring DTM in forested areas. By using high sampling rate, low scanning angle and small beam size, the DTM can be obtained in forested environment from the acquired point clouds.

Kraus and Pfeifer (1998) developed a DTM algorithm based on distinguishing laser points into terrain points and non-terrain points using an iterative prediction of the DTM and weights attached to each laser point depending on the vertical distance between the expected DTM level and the corresponding laser point. Pyysalo (2000) developed a modified recursive classification method for DTM extraction, where all points within 60 cm vertical distance from the lowest expected ground level were included equally in the next DTM model calculation. Axelsson (1999, 2000, 2001) developed a progressive TIN densification method. Elmqvist (2001) estimated the ground surface by employing active shape models by means of energy minimization. The active shape model behaves like a membrane floating up from underneath the data points. The energy function is a weighted combination of internal and external forces. The start state is a plane below the lowest point in the data set. Sithole (2001) and Vosselman and Maas (2001) developed a slope-based filtering technique, which works by pushing up vertically a structuring element. In the method by Wack and Wimmer (2002) non-terrain raster elements are detected in a hierarchical approach that is loosely based on a block-minimum algorithm. An empirical comparison of the methods is depicted in detail in Sithole and Vosselman (2004).

The quality of DTM derived from laser scanning is influenced by a large number of other factors, the reader is referred to the introduction of Yu et al. (2005). From the users point of view, the most relevant issues in the specifications of the data acquisition are date, point density, flight altitude and scan angle. The scan angle and flight altitude affect the point density, the discussion of the effect of the scan angle can be found in Ahokas et al. (2005).

In central Europe, typical requirement for the laser acquisition is to use last pulse mode under leaf-off conditions. However, optimum season for such can be relatively short, e.g. a few weeks especially when snow arrives late in the winter. In Finland the snow cover lasts from October-December to March-May making the leaf-off period in Finland relatively short in spring for laser surveys (2-5 weeks). In autumn, the undergrowth stays high until the snow falls.

The flight altitude is a practical way of the reducing the costs of the acquisition for a known system. By doubling the flight altitude, the density of the data is reduced. For high frequency systems, this also means reduction of the applied pulse repetition frequency (e.g. Optech 3100), since present systems allow a single pulse traveling to and from the object.

Vegetation has an effect on the DTM. The denser the canopy, the smaller the number of ground hits. In Yu et al. (2005) the effect of the trees was analyzed with the first pulse data.

There have been several empirical studies on DTM quality with laser scanning (e.g. Ahokas et al, 2003; Hodgson and Bresnahan, 2004; Hyyppä et al., 2000; Kraus and Pfeifer, 1998; Pereira and Janssen, 1999; Reutebuch et al, 2003). However, most effects (e.g. date, flight altitude) have not been carefully analyzed, and, it is impossible to derive this information by just comparing results of various studies in various conditions.

Therefore, this paper focuses on factors affecting the DTM in boreal forest conditions, especially the effect of the date, flight altitude, pulse mode, terrain slope, forest cover and plot variation are discussed on the DTM accuracy.

2. TEST DATA

The test site was located in a state owned forest area of approximately 50 hectares located in Kalkkinen, southern Finland, 130 km north of Helsinki. The 2-km-by-0.5-km intensive study area situated about 110 m above sea level, with slopes ranging between 0 and 66^{o} and with 87 % of forest cover dominated by species such as spruce, pine and birch, was collected with Toposys I in 1998 and 2000, and with Toposys II in 2003. In all campaigns, the pulse repetition frequency (83 kHz), maximum scan angle (±7.1°), beam size (1 mrad) and wavelength of the system (wavelength of 1.5 µm) remained constant. The major difference between the Toposys I and II was the possibility to record first and last pulse simultaneously in the version II. Since the measurements were recorded at various times of the season, i.e. May 14th 2003 (leaf-off), June 14th 2000 (leaf-on, low development of undergrowth), and September 2nd 1998 (leaf-on, high undergrowth), it was possible to estimate the effect of leaves and undergrowth at boreal forest zone. That was performed using the high pulse density point cloud (8-10 pulses per m^2) obtained from 400 m flight altitude in each acquisition. The effect of the flight altitude was studied using the flight altitudes of 400, 800 and 1500 m above ground level collected in 2003 providing nominal pulse densities of 8-10, 4-5 and 2-3 pulses per m^2.

3. REFERENCE DATA

3.1 Reference Measurements

Eight test plots were chosen so that they represented different types of forest and terrain elevation in the forested area. Each test plot was about 30 m by 30 m in size. Reference data were produced by tacheometer and GPS measurements.

Coordinates for test plot corners were measured in October and November 2001 using Leica SR530 GPS equipment. Measurements were carried out partly as Real Time Kinematic (RTK) GPS and partly as static GPS measurements. For all GPS measurements the same reference point was used. GPS measurements were controlled by measuring one known height point daily and by measuring some corner points several times. On some locations also RTK fix was obtained. Static measurements enabled comparison between RTK coordinates and coordinates obtained by post-processing.

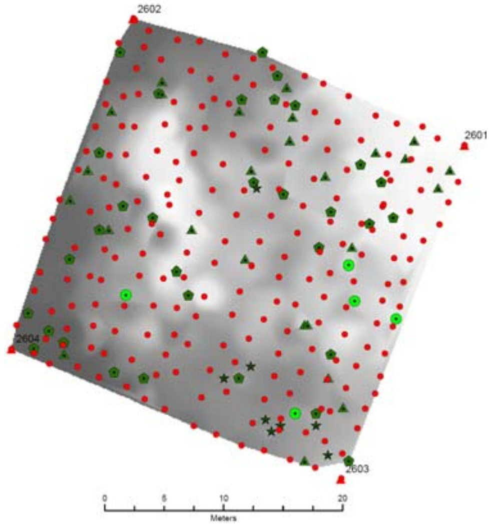

Figure 1. The distribution of reference measurement within the plot. Small red dots refer to terrain heights and larger green dots refer to tree locations. In all locations, terrain coordinates and the heights were recorded.

Measured test plot corners were used as known points for tacheometer measurements in October 2002. Because there were no other permanent marks for test plot corners than wooden poles and measurements were carried out to the ground next to the poles, the absolute accuracy of tacheometer measurements was estimated to be about 10-15 cm while relative accuracy within a test plot should be better than 5 cm.

Theodolite Wild T2002 with Distometer Di2002 was used to measure tree locations and terrain height points. Typically, coordinates for tree location in north and east direction were measured to the centre of the trunk and the height was measured next to the tree, thus making it possible to use the tree coordinates for DTM determination as well. In most cases, DTMs were measured as a grid of ground points. Measured points were distributed evenly inside the plots with a distance from each other of about 2 m. Altogether 2119 points were recorded.

3.2 Test Plot Characteristics

Test plot 5: Mainly tall spruces together with few tall birches, on one corner a more dense area of smaller spruces, no bushes. The plot is located on a gentle slope and terrain is very smooth.

Test plot 9: Tall birches and smaller spruces below them, practically no undergrowth. Terrain is fairly smooth and gentle slope.

Test plot 10: Mainly full-grown trees of various species, some bushes in the undergrowth. A small cliff and fairly large height differences in the plot.

Test plot 14: Mainly full-grown trees of various species together with smaller and denser undergrowth of trees. Middle part of the plot flat, steep slopes of few meters on two sides.

Test plot 22: Mainly tall pines, main part of the plot on top of a small hill, steep slope on one side.

Test plot 26: Mainly full-grown trees of various species. Some dense bushes in the undergrowth. Terrain is fairly flat.

Test plot 30: Mainly saplings of various species, partly very dense growth. Test plot is located on a hillside, so large height differences within the plot.

Test plot 34: Mainly tall birches together with some tall pines and spruces. Plot is located on a gentle slope, otherwise flat terrain.

4. METHODOLOGY

4.1 Creation of DTM from Laser Data

Systematic shifts in height data between different flights were corrected using ground control heights of flat surfaces and buildings. After coordinate transformations, geoid correction, strip adjustment and systematic shift correction laser point clouds were classified by TerraScan software (see www.terrasolid.fi) to separate the ground points from other points (low and high vegetation).

The ground points were triangulated using TIN densification method developed by Axelsson (2000), where surface was allowed to fluctuate within certain values, controlled by minimum description length, constrained spline functions, and active countour models for elevation differences. Ground points were connected in a TIN. A sparse TIN was derived from neighbourhood minima, and then progressively densified to the laser point cloud. In each iteration, points are added to the TIN, if they are within defined thresholds. The method has been implemented to Terrascan software.

4.2 Evaluation of the Laser DTM

The accuracy of the laser DTM was evaluated by comparing the DTM values with the corresponding reference points obtained by field measurements. Systematic elevation error was calculated as mean height differences between laser DTMs and field measurements, whereas the random error was obtained from standard deviation (STD) of the difference.

The effect of tree cover was calculated as follows: terrain points were considered to be either in an open area or under a tree. The reader is referred to Yu et al. (2005) for more detail.

5. RESULTS

5.1 Effect of the Date

The random errors varied from test site to test site. With the last pulse, the measurements conducted during leaf-off period resulted in the smallest random error, i.e. 7-17 cm, in most of the plots. The use of a non-optimal season resulted in increased random error by 3 to 9 cm (units). In general the differences were smaller than expected. Plot 14 has dense undergrowth and hence all date resulted in inferior performance. Plot 30 has dense high vegetation (mixed species), which was more difficult during leaf-on period.

Figures 2 and 3 show the random error of the DTM derivation using first and last pulse.

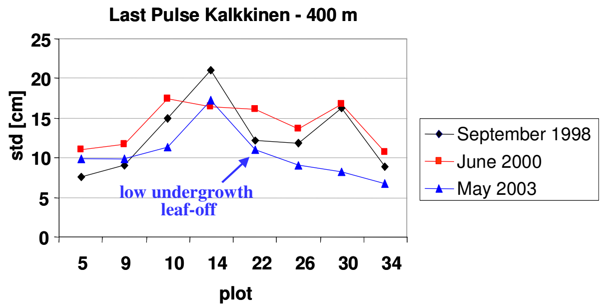

Figure 2. The effect of the date on the DTM random error using last pulse.

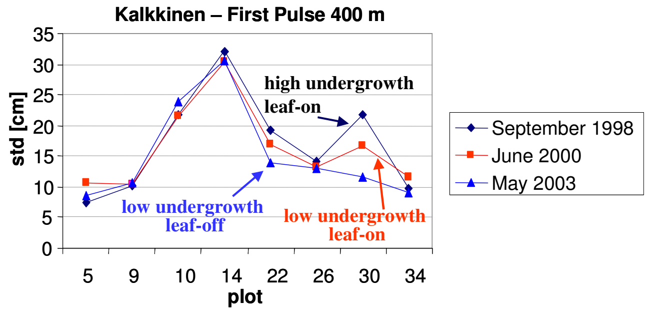

Figure 3. The effect of the date on the DTM random error using first pulse.

Even with the first pulse and with non-optimal season the obtained results were good.

5.2 Effect of Flight Height

By increasing the flight altitude, the density of the pulse decreases in the across-track direction. From the altitudes of 400, 800 and 1500 m, the across-track point spacings were 0.80, 1.6 and 3.0 m, respectively. The corresponding beam sizes on the ground were 0.4, 0.8 and 1.5 m. Therefore, the effect of the flight altitude is a combined effect of the across-track point spacing reduction and increase in the beam size. Figure 4 summarizes the results.

With Toposys II (i.e. acquisition done in 2003), the first and last pulse modes were acquired simultaneously. The systematic shifts with respect to ground references are shown in Figure 4. At 400 m, the first pulse overestimated DTM approximately 9 cm compared to the last pulse. In 800 m, the difference was 4 cm, and at 1500 m, the difference was –1 cm. This is most likely due to the effect of the beam size and sensitivity. At 400 m, the small beam more easily finds the undergrowth at first pulse. The small pits are also found if the system is sensitive enough. With a larger beam and from a higher altitude (lower return pulse level), the difference between the first and last pulse decreases.

The random errors obviously increase as flight altitude increases. This is mainly due to the decrease of the pulse density and increase in the planimetric error (for non-flat surface).

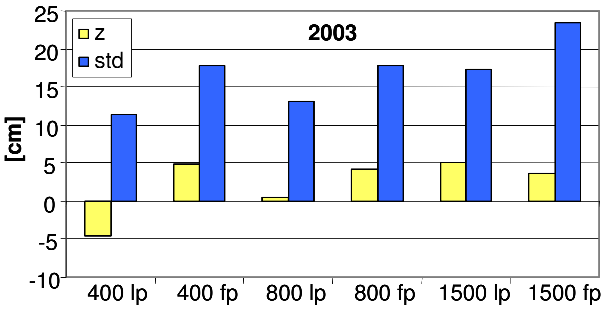

Figure 4. The DTM systematic and random errors from different flight altitudes at first and last pulse modes.

It can be concluded that the effect of the first versus last pulse on the errors is higher than doubling the flight altitude. The effect is approximately the same as making the flight altitude four times as high. An impressive random error of approximately 18 cm was obtained for hilly boreal forest area (relatively dense concerning forest cover) from the height of 1500 m with the last pulse.

5.3 Effect of Terrain Slope

Effects of terrain slopes on laser DTMs are shown in Figure 5 for laser points, interpolated points in raster model (0.5 m grid) and for all points. Accuracy deteriorates gradually with the increasing slope. Elevation errors for under tree areas increased more dramatically for slopes greater than 15^o degrees. The results indicate that interpolation error is an important factor influencing the accuracy of laser DTMs and as slope increases, interpolation errors also increase.

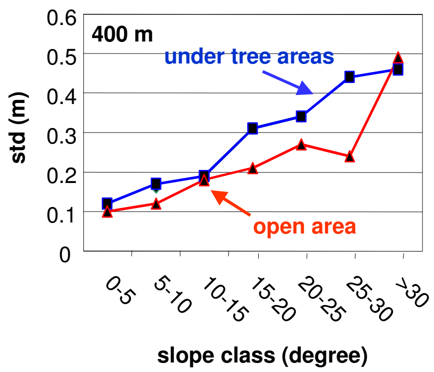

Figure 5. Effect of terrain slope on DTM random error.

5.4 Effect of Forest Cover

In order to evaluate the effect of forest cover on DTM derivation accuracy, tree-cover effects were examined. All plots were segmented into small regions corresponding to either open areas (no vegetation above) or under tree areas. Also the DTM beside the trunk was measured.

The effect of forest cover is higher when moving closer to the trunk (Figure 6). The maximum systematic difference due to the cover is 8 cm in the 400 m last pulse datasets. The random error increases 2 to 3 cm under the tree and it is 2-5 cm higher near the trunk with the last pulse, which indicates that the ground elevation can be reliably detected even under trees. With the first pulse, see the analysis in Yu et al. (2005).

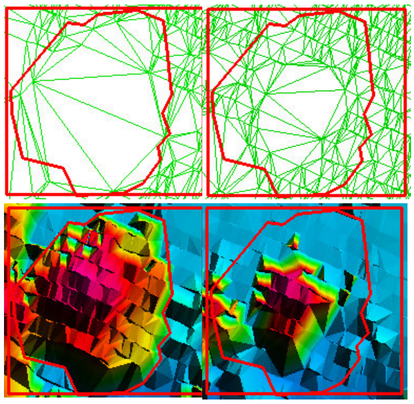

Figure 6. Digital terrain model using TIN. First pulse (top left) and last pulse (top right). (Below is shown) the surface model of the tree crown with first pulse (below left) and last pulse (below right).

5.5 Within Plot Variation

Within plot variation is mainly caused by the variation in the terrain slope, undergrowth and vegetation cover. Figure 7 shows both systematic error and random error variation analysed for example plots.

The results show that the systematic error variation is higher than the random error variation. The former is caused by changes in undergrowth, remaining errors in strip orientation and problems in the calibration of the elevation level. For example, for the test plot number 9, which is fairly smooth with gentle slope, the systematic error range between –18 to 10 cm, where-as the random error (with all flight altitudes and pulse modes and dates) ranges from 7 to 11 cm. Systematic error variation was higher than the random error variation except for the test site 14, which includes dense undergrowth and steep slopes.

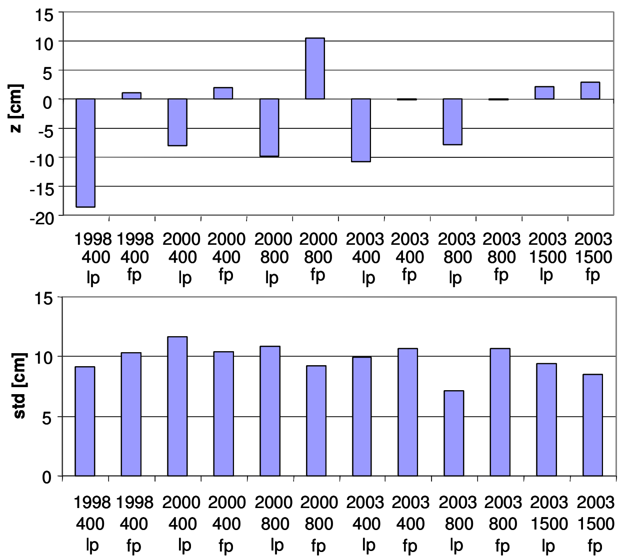

Figure 7. Within systematic (top) and random (below) plot variation for plot 9.

6. CONCLUSIONS

This paper analysed the effects of the date, flight altitude, pulse mode, terrain slope, forest cover and within plot variation on the DTM accuracy at boreal forest zone. The following conclusions could be drawn from the high-density data:

- At boreal forest zone, random errors of less than 20 cm can be obtained in most conditions for non-steep terrain.
- The increase of flight altitude from 400 to 1500 m increased the random error of DTM derivation from 12 to 18 cm (i.e. 50%).
- The difference of using first or last pulse causes a corresponding random error difference, i.e. 5 cm.
- There are systematic shifts in the elevation models derived at various flight altitudes. It is expected that the beam size and sensitivity of the laser system cause this systematic behaviour. Additionally, the systematic shifts between last and first pulse are significant.
- The difference in DTMs derived at optimum and non-optimal season conditions is typically less than 5 cm for high-density data (this is not relevant for most applications). In stand consisting of deciduous trees, the effects are the highest. Use of non-optimal flying season mainly causes that details of the terrain elevation can not been measured in the same accuracy.
- The random error increases with increasing terrain slope.
- The effect of forest cover is higher when moving closer to the trunk. The random error is 2-5 cm higher.
- The results are site dependent, i.e. the accuracy varies as function of site conditions (slopes, undergrowth, forest cover).

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