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Laser Scanner Derived Digital Terrain Models for Highway Planning in Forested Areas

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Abstract. *High-quality digital terrain models (DTM) are needed in road and street planning. Collection of accurate terrain information with conventional photogrammetric or geodetic methods is time consuming and expensive and, thus, typically not carried out over large areas. Airborne laser scanning (ALS) has become an established tool for acquiring digital terrain models in forested and urban areas, which means it is a cost-effective way of producing accurate information on the surrounding environment for road planning and other design purposes. The quality of DTM derived from laser scanning is influenced by laser acquisition parameters. This study analyses these factors affecting the quality of DTM accuracy and discusses the results from the highway planning perspective. The results are based on several laser campaigns in forested areas conducted in Finland between 1998 and 2004.*

Keywords: *digital terrain model, DTM, airborne laser scanning, quality, forests, highway planning*

1 Background and Motivation for the Research

The digital terrain model (DTM) is the basis for interactive computer-based road design, which is needed in the design of horizontal and vertical geometry, road structure, draining, mass calculation, and in environmental impact analysis and in visualizing the plan. The existing databases, GIS and digitized maps are traditionally used for general planning. The level of planning, when moving from general planning to more detailed design, determines the required accuracy of the DTM.

The collection of accurate 3D information using conventional photogrammetric and geodetic methods, such as Real-Time Kinematic GPS (RTK-GPS), stereoscopic photogrammetry and tacheometer measurements, is time-consuming and costly. These methods are, however, used for measuring breaklines in steep terrain and elevations of selected terrain points. The existing national DTMs that have often been created with photogrammetric techniques (elevation accuracy 1–2 m) are generally not sufficient for most of these applications.

Airborne laser scanning (ALS) is a method based on laser (lidar) range measurements from an aircraft. The range measurement combined with the known orientation information of the measuring sensor results in 3D point clouds that correspond to the shapes of the reflecting targets. The orientation is determined from the direct orientation sensors: the position from differential GPS and the position and rotations from inertial devices. Modern ALS allows at least 100 000 range measurements to be taken per second. With a flight altitude of 1 km and scan angle of 10^o, a pulse density of four pulses per m^2 can be obtained at typical flight speeds. On an average day, several hundreds of km^2 of terrain can be surveyed. After the survey, the 3D point clouds are processed in order to create digital surface models (DSM) and digital terrain models (DTM). In the case of forests, the first pulse usually bounces back off the top of the canopy or the ground and the last echo tends to bounce back from the ground under the vegetation. Laser scanning is relatively inexpensive, especially when the accuracy of laser derived products is taken into account and they are compared with other methods. Today, it costs from 100 to 4,000 €/km^2 to carry out laser scanning on areas from 10 000 to 1 km^2, respectively, with a relatively dense point cloud (3–5 pts per m^2). Airborne systems, such as Toposys, Optech and Leica, are used for mapping large consistent areas. DTM surveying of existing roads could also be carried out using a helicopter-borne laser, such as TopEye, which is also equipped with a digital camera.

Laser scanning has become an established tool for the creation of national DTMs (Vosselman, 2000) and is used at surveying and mapping agencies (Petzold et al., 1999). Laser scanning is the data acquisition and monitoring technique which has greatest potential for providing support for road and transportation planning. Vast data sets, which may even cover entire countries, challenge existing manners of proceeding. For example, laser scanner data already existed for the whole of the Netherlands in the late 1990s, for Switzerland in the 2000s, and large parts of southern Germany. Data also exists, or will be generated in the next few years, for most of the large cities in Finland including Helsinki. There are plans for airborne laser data to be compiled for the whole of southern Finland in order to improve the national DTM that is currently in existence. These point clouds can be used to improve other products as well.

The quality of laser scanning derived digital terrain models is influenced by a number of factors, which can be grouped as follows: errors caused by the laser system, data characteristics, data processing, and errors due to the characteristics of the target. (e.g. Hyyppä and Hyyppä, 2003). From the road planning point of view, the most relevant issues regarding the specifications of the data acquisition are acquisition parameters, such as the date, point density, flight altitude and scan angle.

There have been several empirical studies on the quality of DTMs produced using laser scanning (e.g. Kraus and Pfeifer, 1998; Gomes-Pereira and

Wicherson, 1999; Pereira and Janssen, 1999; Hyyppä et al., 2000; Huising and Pereira, 1998; Ahokas et al., 2003; Reutebuch et al., 2003; Hyyppä and Hyyppä, 2003; Hodgson and Bresnahan, 2004; Hyyppä et al. 2005). Results show that the accuracy of derived elevations is about 10–15 cm depending on surface, slope, laser device, flying height etc. Laser scanning produces optimal results when used in the early stages of initial route location and formulation of alternatives. When laser scanning is used for detailed road planning, it is necessary to optimize the flying altitude and create new algorithms to smooth and classify the laser data.

Shrestra et al. (2000) have used laser data for highway mapping and to generate DTMs. In both the Netherlands and Canada (Pereira and Jansen, 1999; Berg and Ferguson, 2000, 2001) studies were made to determine the suitability of laser scanning in highway planning and design. In highway planning, difficulties were encountered with breaklines (Brügelmann, 2000; Gomes-Pereira and Wicherson, 1999; Gomes-Pereira and Jansen, 1999).

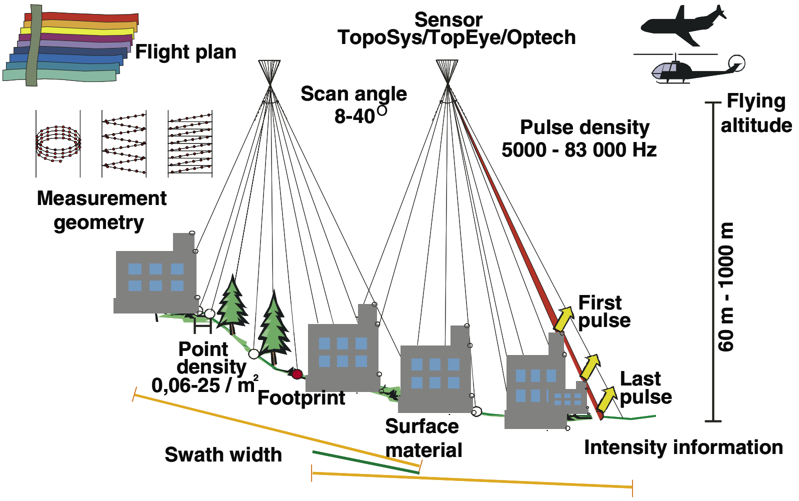

Figure 1. Factors affecting the quality of laser scanning.

However, several factors, such as the date and flight altitude, which both affect density, have not been carefully analysed. The main objective of this paper was to study the effects of these factors on the creation of DTMs and to discuss the applicability of these results to street and road design.

2 Material and methods

2.1 Test sites and laser scanner data

The forested test site was located in a state-owned forest area of approximately 50 hectares located in Kalkkinen, in southern Finland, 130 km north of Helsinki. Data for the 2 km by 0.5 km intensive study area situated about 110 m above sea level, with slopes ranging between 0° and 66°, with 87% of forest cover, with species such as spruce, pine and birch, was collected with laser scanning data from Toposys I and II systems in 1998, 2000, and 2003. In all campaigns, the maximum pulse repetition frequency (PRF) (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 Toposys I and II was the option of recording the first and last pulse simultaneously in version II. Since the measurements were recorded at various times of the year, i.e. May 14, 2003 (no leaves), June 14, 2000 (leaves on trees, low density of undergrowth), and September 2, 1998 (leaves on trees, high density of undergrowth), it was possible to estimate the effect of leaves and undergrowth at the boreal forest zone. This was performed using the high pulse density point cloud (8–10 pulses per m^2) obtained from a flight altitude of 400 m above ground level (AGL) in each acquisition. The effect of the flight altitude was studied using flight altitudes of 400, 800 and 1,500 m (AGL) collected in 2003 providing nominal pulse densities of 8–10, 4–5 and 2–3 pulses per m^2.

2.2 Field measurements

Eight test plots were chosen in Kalkkinen to represent different types of forest and terrain elevation in the forested area. Each test plot was about 30 m by 30 m. Reference data were produced by tacheometer and RTK-GPS measurements. Coordinates for test plot corners were measured in October and November 2001 using Leica SR530 GPS-equipment with an accuracy typically higher than 3–4 cm. Measured test plot corners were used as known points for tacheometer measurements in October 2002. A Wild T2002 theodolite with a Di2002 Distometer was used to measure tree locations and terrain height points. Coordinates for tree locations in the north and east were typically measured at the centre of the trunk, and height was measured next to the tree thus also making it possible to use tree coordinates when determining DTMs. In most cases DTMs were measured as a grid of ground points. Measured points were distributed evenly inside the plots at a distance of about 2 m from each other. Altogether 2,119 points were recorded. The relative accuracy of each measured point was expected to be better than 5 cm.

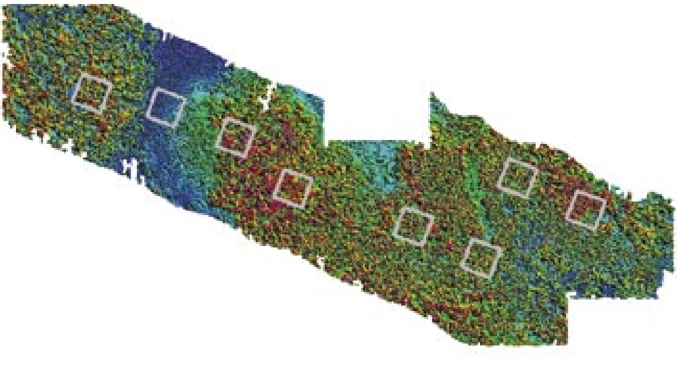

Figure 2. *Digital surface model produced with the eight test plots.*

2.3 Methods

Preprocessing of laser points. The surveys resulted in acquiring raw measurement data as follows: GPS coordinates were acquired from the reference station, GPS and INS information from the aircraft, including laser hits, synchronization, and intensity as well as images. The preprocessing of the data into georeferenced point cloud were carried out by Toposys GmbH. Data were converted into the Finnish YKJ system using conventional formulas. The height values were corrected and taken into account the geoid. Initial strip adjustment was carried out to correct the height levels of each strip. Systematic errors were minimized using the flat surfaces of known elevations.

Classification. The points were classified into ground, vegetation and building points. Each strip was processed separately. Classification started by locating ‘low points’ using neighbourhood information. Then the iterative ground classification process was started using initial point logic controlling building size, terrain angle, iteration angle and distance. The ground points were triangulated using the TIN densification method developed by Axelsson (2001), where surface was allowed to fluctuate within certain values, controlled by minimum description length, constrained spline functions, and active contour 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. Points were added to the TIN in every iteration, if they were within defined thresholds. The method has been implemented using Terrascan software. The DTM was calculated using classified ground points for each individual strip.

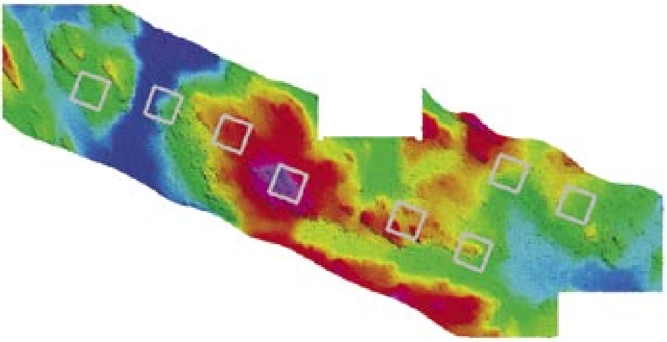

Figure 3. *Produced digital terrain model.*

Segmentation. The effect of tree cover was calculated as follows: high vegetation points were segmented using first pulse data considered to be either in an open area or under a tree.

Verification. To evaluate laser DTM accuracy, the differences between laser-derived elevations and field measurements at the location of reference points were calculated. The vertical accuracy of laser scanning was evaluated using a root mean square error test

$$RMSE_z = \sqrt{\frac{\sum(Z_{ground} - Z_{reference})^2}{n}} \tag{1}$$

where $Z_{reference}$ is measured to find the elevation using a tacheometer or RTK and Z_{ground} is the corresponding elevation interpolated from TIN ground, and n is the number of reference points used. Systematic elevation error (dz) 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.

3 Results

By increasing the flight altitude, the density of the pulse decreased in the cross-track direction. From altitudes of 400, 800 and 1,500 m, the cross-track point spacings were 0.80, 1.6 and 3.0 m, respectively. The corresponding beam sizes at ground-level were 0.4, 0.8 and 1.5 m. Therefore, the effect of the flight altitude results from the combined impact of the cross-track point spacing reduction and increase in the beam size.

With Toposys II (i.e. 2003), the first and last pulse modes were acquired simultaneously. The systematic shifts with respect to ground references are shown in Figure 4 with no leaves and low development of undergrowth. At 400 m, the first pulse overestimated DTM by approximately 9 cm compared with the last pulse. At 800 m, the difference was 4 cm, and at 1,500 m, the difference was –1 cm. This is most likely to result from the effect of beam size and sensitivity. At 400 m, the small beam finds the undergrowth more easily with the first pulse. Small pits are also found easily if the system is sensitive enough. The difference between the first and last pulse decreases with a larger beam and from a higher altitude (lower return pulse level). The random errors obviously increase as flight altitude increases. This is mainly due to the decrease in pulse density and the increase in planimetric errors.

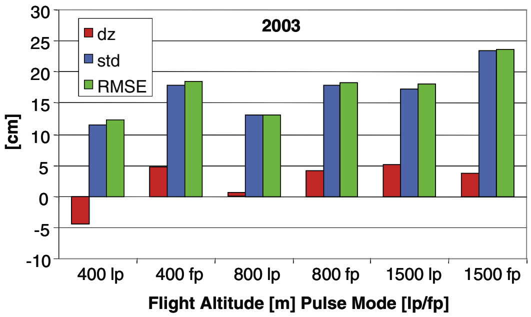

Figure 4. *The elevation errors of the DTM divided into systematic (dz) and random components (std) from different flight altitudes at first (fp) and last pulse (lp) modes.*

It can be concluded that the difference between first and last pulse DTMs is almost the same as making the flight altitude four times as high at the last pulse mode. An impressive random error of approximately 18 cm was obtained for a hilly boreal forest area from a height of 1,500 m on the last pulse. Figure 5 shows the accuracy between the plots. Variation between plots is mainly caused by the variation in the slope of the terrain, undergrowth and vegetation cover. It can be concluded that canopy and terrain conditions have a greater effect on accuracy than laser acquisition parameters.

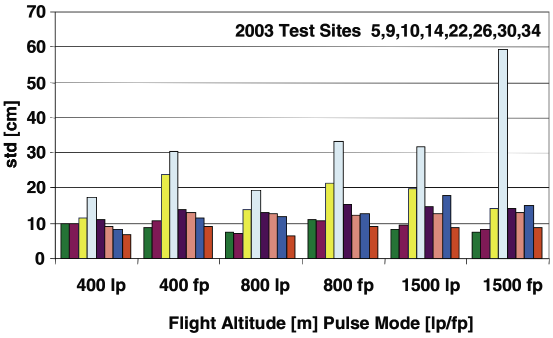

Figure 5. *Random errors in DTMs for each test site.*

The difference between first and last pulse DTMs is illustrated in Figure 6. Fewer ground points in the first pulse mode obviously result in lower accuracy of the DTM. The separation of trees seems to be more feasible with the last pulse mode than with the first pulse.

In early summer (June, leaves but the development of undergrowth was still low), the systematic overestimations of the triangulated DTM in Kalkkinen were 19 cm and 2 cm for the first and last pulse, respectively for data from 400 m, and the corresponding standard deviations were 19 cm and 15 cm, respectively, Figure 7. The systematic shift between the pulse modes was then 17 cm. It should be noted that the systematic shift may change during the growing seasons due to changes in the undergrowth, which, in this analysis, is mainly due to the leaves in the undergrowth. The corresponding systematic shift at 800 m was 21 cm and no similar decrease of the systematic errors as a result of beam size was observed as it was in the previous analysis. It is possible that the separate flights for first and last pulse in 2000 may have had some impact on the results. The rise in random errors was 3 cm units for 800 m.

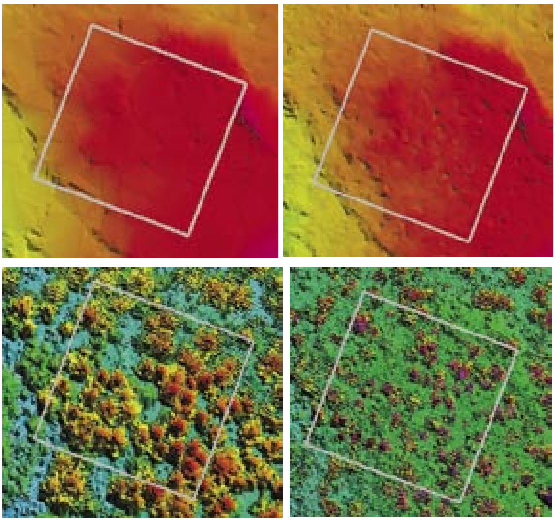

Figure 6. *Results when using first (left) and last pulse (right) modes in DTM (above) and derived canopy models (below).*

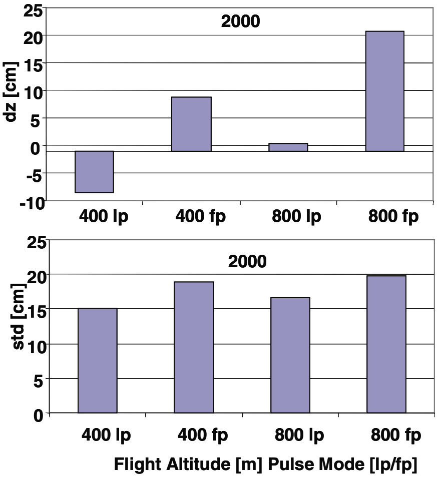

Figure 7. *The systematic and random errors between first pulse and last pulse modes, altitudes 400 and 800 m AGL, year 2000 acquisition. (lp refers to last pulse and fp to first pulse mode.)*

The canopy is more dense closer to the trunk (Figure 8). Because lasers are not able to see through canopies which are too dense, this causes an increased need for the use of interpolating methods in order to create continuous DTMs. The maximum systematic difference as a result of tree cover is 8 cm in the 400 m last pulse datasets. The random error increases by 2 to 3 cm units under the tree and is 2–5 cm units higher near the trunk with the last pulse, which indicates that ground elevation can be reliably detected even under trees.

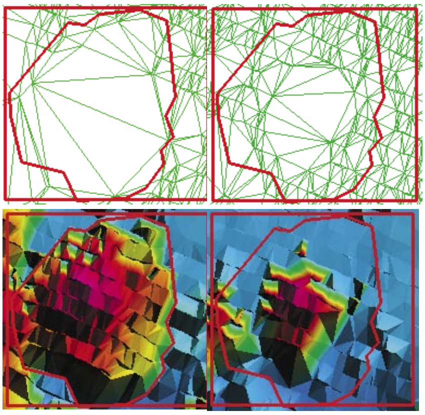

Figure 8. *Digital terrain model under a tree using a TIN. First pulse (top left) and last pulse (top right). The images below show the surface model of the tree crown with first pulse (below left) and last pulse (below right).*

Seasonal changes also affect the random errors in the DTM. With the last pulse, those measurements conducted when the trees had no leaves resulted in the smallest random error, i.e. 7–17 cm, in most of the plots, Figure 9. Scanning carried out during a season with the poorest conditions resulted in random errors increasing by 3 to 9 cm. In general, the differences were smaller than expected. Plot 14 has dense undergrowth and steep slopes which results in an inferior performance in all three acquisitions. Plot 30 has dense vegetation (mixed species) which poses greater difficulty during the period when trees have leaves.

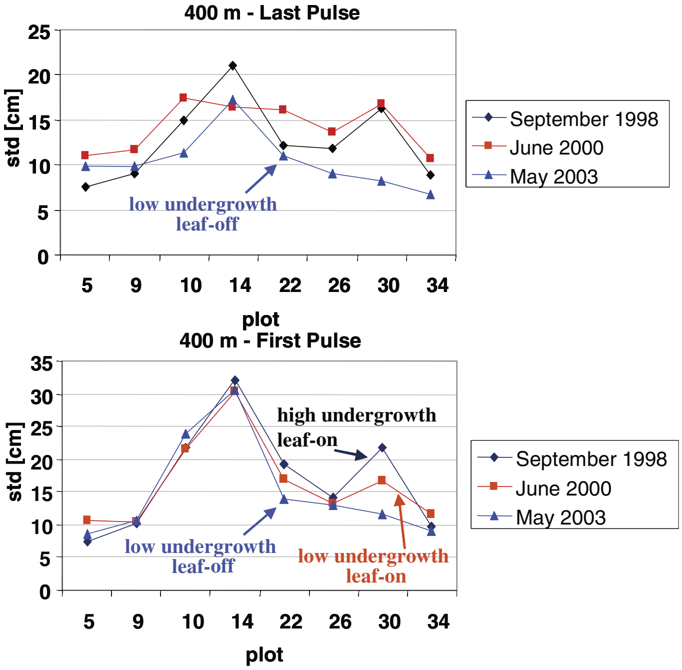

Figure 9. *The impact of the date on random error in DTMs when using last pulse and first pulse.*

4 Discussion

New roads are typically constructed in forested areas (more than 70% of Finland is covered by forests). The starting point for all planning is the DTM. The accuracy of the DTM determines the amount of masses that need to be transferred from one place to another. The accuracy of laser-derived models in forest-covered terrain was depicted. Kalkkinen can be considered a challenging area for testing DTMs due to its small hills and tall trees. With laser scanning, the user has to specify the model requirement e.g. the most accurate model or the most economic. The parameters which have an effect on accuracy are flight altitude, the sensor used, scanning angle, and applied pulse mode. Flight altitude has a direct impact on swath width, beam size and pulse density. The specification of fight altitude is the most important way to optimize costs, accuracy and to meet the requirements of the user. It is possible to use several flight altitudes to guarantee the required accuracy. The forest conditions (density, structure, canopy coverage, height) affect accuracy. The seasons also have an effect on the accuracy depending on the effects of the trees in the model (leaves on/no leaves, density of the low vegetation /undergrowth).

Due to the good accuracy obtained with laser scanning, strips must be properly adjusted between laser strips. Based on the experience gained in several tests, it can be concluded that crossing strips should be recorded at the end of the actual flight strip in order to calibrate systematic errors. When carrying out corridor-type mapping, the flight lines should be planned to be as linear as possible in order to avoid errors resulting from the plane turning. When crossing strips are considered ineffective, parallel strips in block geometry, Figure 10 (right), is recommended to calibrate out systematic errors. For highway and street design, it is also recommended that two flight altitudes are used, one for getting an exact DTM and the other for mapping the surrounding environment. Alternatively, the intensive area can be recorded by parallel strips in which the intensive area (road) is covered by both strips.

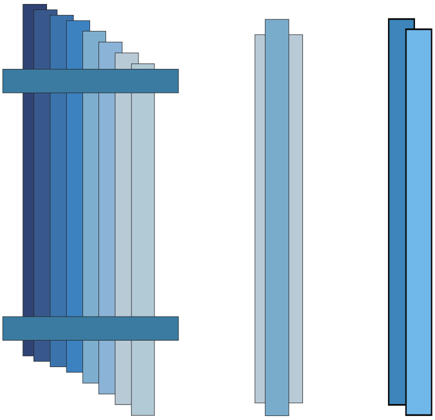

Figure 10. Suggested block geometries for various types of area; suggested geometries for highways and streets is in the centre and on the right.

The advantages of laser scanning for highway, street and road design are as follows.

- The advantage of laser scanning is its capacity to provide a large number of high-quality points. A large number of points allows filtering so that smooth surfaces can be depicted with fewer points, whereas steeper changes in terrain are depicted with high density data.
- 3D presentation of the target, including DTMs and the Canopy Height Model (examples for single trees in Figure 8), offers an efficient way of carrying out visual inspection for highway and street design. These models allow environmental impact assessment and planning of ecological flyovers, e.g. for flying squirrels, to be carried out. Environmental impacts can easily be realized using change detection and two laser acquisitions, one for planning and one for confirmation of the actual project.
- Cut and fill quantities are more precisely estimated during planning stages using laser scanning. Also, preliminary cost calculations are much more accurate using an accurate 3D model. If laser scanning can increase the accuracy of terrain models, quantity calculations and cost estimates will also improve.
- Digital photos and laser scanning give an opportunity to provide all the information required in planning, including breaklines. Images only provide major breaklines whereas laser information gives the height of the breaklines and the height of terrain points.
- Laser scanning can provide the road designer with DTM data faster than traditional photogrammetry. After the survey, data can be processed semi-automatically in a short time.
- Laser scanning decreases the time spent on planning and the amount of work needed. It is also cost-effective, if only the costs of the project that are compared. The final quality can also be improved as a result of the high quality of the initial data.
- It is possible to optimize the construction of new roads using accurate DTMs derived from laser scanning point clouds, but it is also necessary to take the environmental impacts into account.
- The watershed area created using a DTM will be used to clarify the environmental effects caused by a road.
- The customer and data provider should have a joint understanding of the quality of the model, and how it can be accomplished using laser scanning. Even though the customer can order the model based on the specifications of the DTM, such as RMSE and standard error, the pulse density provides information on how detailed the models are. The customer should not receive sparsified point clouds unless this is what they want. It is important to remember that the original georeferenced point cloud has multiple uses.

Countrywide collection of laser scanning, mainly as a result of creating DTMs, is becoming increasingly common. National laser scanning (NLS) which started in the Netherlands, and continued in Switzerland and various states of Germany, and has been discussed in Japan, Sweden, and Finland, provides both terrain and surface models. Data for the Netherlands was collected using sparse point clouds. Point clouds are currently being collected mainly with a density higher than 0.5–1 point per m^2 (e.g. Artuso et al., 2003). In central Europe, countrywide laser data collection for the DTM requires the last pulse mode to be used at times of the year when trees have no leaves in order to guarantee high-quality DTM in forested areas. The permitted flight period extends from November to March in Switzerland (Artuso et al. 2003). Finland is relatively large in area (374 000 km^2) and is characterized by relatively flat topography. More than 190 000 lakes provide a good feature for controlling the terrain model. Carrying out laser scanning over the whole of Finland is a new concept and would be advantageous for highway, street and road planning and maintenance. The costs related to data collection can be significantly reduced if this data is collected for the whole of Finland (i.e. would amount to less than 100 €/km^2).

5 Conclusion

This paper analysed the impacts of date, flight altitude, pulse mode, terrain slope, and forest-cover on the accuracy of DTMs over boreal forest zones. The following conclusions could be drawn from the high-density data:

- According to the studies, laser scanning technology would provide information on terrain that is accurate enough to complete photogrammetry in forested areas.
- In boreal forest zones, random errors of less than 20 cm can be obtained under most conditions for flat terrain.
- The increase of flight altitude from 400 to 1,500 m increased the random errors in DTM derivation from 12 to 18 cm (i.e. 50%).
- The difference between using the first or last pulse results in a corresponding random error difference, i.e. 5 cm.
- There are systematic shifts in the elevation models derived at various flight altitudes. Beam size and the sensitivity of the laser system are assumed to determine this systematic behaviour. Additionally, the systematic shifts between last and first pulse are significant.
- The difference between DTMs derived during seasons with optimum conditions as opposed to poorest conditions is typically less than 5 cm with high-density data. In stands containing deciduous trees, the effects are most noticeable. Laser scanning carried out during seasons with the poorest conditions mainly results in details of the terrain elevation not being measured with the same accuracy.
- The impact of forest cover is greater nearer the trunk. The random error is 2–5 cm greater near trunks.
- The results are site dependent, i.e. the (obtained) accuracy varies as does the function of site conditions (slopes, undergrowth, forest cover).

Block geometries for various types of areas, including corridor-type highway areas were suggested and implications for highway, street and road design were discussed. Highway and street design was suggested as a potential application for countrywide laser scanning in Finland.

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