APPLICABILITY OF FIRST PULSE DERIVED DIGITAL TERRAIN MODELS FOR BOREAL FOREST STUDIES

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ABSTRACT:

Detailed high-resolution digital terrain models (DTM) can be obtained using airborne laser scanner data. This paper evaluates the accuracy of DTM derived from first return of laser scanner data for forest studies. Study area is located in a boreal forest zone. The data were acquired with TopoSys-1 under leaf-on condition. The study shows that the use of first pulse data for DTM generation in boreal forest zone results in comparable random errors as last pulse derived DTM. Even under leaf-on conditions, the random errors were typically less than 20 cm. The major difference in the performance is the small systematic elevation shift of the order of 10-20 cm in the first pulse DTM compared to the use of the last pulse. The effects of tree species, terrain slope, the vegetation covers and interpolation on first pulse-derived DTM were also investigated.

1. INTRODUCTION

In the past few years, airborne laser scanning has become a very important technique for the acquisition of accurate digital terrain models (DTM), especially in forested areas where traditional techniques, such as photogrammetric stereo measurements, often fail. With the capacity to penetrate forest canopies due to its high measurement density, laser scanning can directly measure the terrain elevation beneath the aircraft. Nowadays, laser scanning has become an established tool for the creation of DTMs in several countries (Vosselman, 2000) and at surveying and mapping agencies (Petzold et al., 1999).

Also the use of laser scanning for forest studies has increased exponentially between year 2000 and 2005. Presently, most used technique to obtain DSM (Digital Surface Model) relevant to treetops is to calculate the TIN of the highest reflections (i.e. by taking the highest point within a defined neighbourhood) and interpolate missing points e.g. by Delaunay triangulation. The canopy height model (CHM) of the forest area is then obtained by subtracting the DTM from the corresponding DSM. The crown DSM is typically calculated by means of the first pulse echo and DTM with the last pulse echo. However, in boreal forest zone, the use of first pulse data even for DTM generation is increasing, since the accuracy obtained for the CHM has typically been about 1 m and it has been expected that DTM can be obtained with favourable conditions (boreal forest area) using first pulse with reasonably high accuracy (20-30 cm). From the practical point of view of forest measurements and inventory, it would make the process easier (data reduction 50%), if the first pulse data alone would derive an accurate CHM including the DTM. Therefore, the systematic and random errors related to the DTM derivation using first pulse needs to be studied in detail. On the contrary, if both first and last pulse data are applied in the process, both of them should also been used especially for DSM and possibly for DTM derivation in order to increase pulse density and accuracy. That is not presently done. Thus, in any case there is a need to improve present processes in forest measurements, and the quality related to first pulse derived DTM is of high importance for forest studies from practical point of view.

The quality of DTM derived from laser scanning is influenced by a number of factors which can be grouped as follows; errors caused by the laser system (laser instrument, GPS and INS) and data characteristics (e.g. first/last pulse, point density, flight height, scan angle), errors created during processing of the data (interpolation errors, filtering errors, errors caused by improper break-line detection, segmentation and smoothing of the data), and errors due to characteristics of the target (type of the terrain, flatness of the terrain, density of the canopy above).

Position and orientation errors or errors in the integration of GPS/IMU and laser are usually removed by strip adjustment or by error modeling (Huising et al., 1998; Crombaghs et al., 2000; Vosselman and Maas, 2001; Burman, 2000; Roggero, 2001; Schenk, 2001). A detailed description of laser system errors can be found in Baltsavias (1999) and Schenk (2001). System parameters, such as flight height, pulse mode, maximum scan angle, and pulse rate, have an impact on laser data characteristics so that they have to be optimized for obtaining high-quality laser data with respect to the visibility of small objects and penetration rate through the forest. This can be achieved through careful mission planning and operation.

The errors created during processing of the data depend largely on applied algorithm and terrain type. In order to create accurate DTMs from laser scanning data, filtering of both blunders and undesired objects is required (Axelsson, 2000; Hyyppä et al., 2000; Kraus and Pfeifer, 1998; Ruppert et al., 2000; Vosselman, 2000). These filtering methods work either on raw data points or on raster images created from them. The latter approach has the disadvantage of being influenced by interpolation errors (Wehr and Lohr, 1999; Llody and Atkinson, 2002; Hodgson and Bresnahan, 2004). For well-defined areas, there are no significant differences in the performance of various DTM algorithms. The problems remain mainly with low vegetation on slopes and complex situations in urban areas (Ahokas et al., 2003). Sithole and Vosselman (2004) suggested that filtering using segmentation, and understanding of the context of the landscape being filtered might be one way to overcome this challenge.

With respect to type of terrain and surface, Raber et al. (2002a) and Hodgson et al. (2003) found that land-cover types were a significant factor that influences the accuracy of laser DTM in forested areas. Pfeifer et al. (2001) reported RMSE ranging from 2.4 cm to 14.5 cm for different types of surface in an urban area. The more open the area, the more accurate the laser-derived DTM. The impact of terrain slope on laser DTM was examined by Hyyppä et al. (2000) and Hodgson et al. (2003). Hodgson et al. (2003) hypothetically suggested that if land cover is the dominant source of error and these land covers are typically found on larger slopes, then terrain slope may be mistakenly identified as major source of error. Hyyppä et al. (2000) suggested that in general, DTM accuracy deteriorated with increasing slope. Raber et al. (2002a) suggested that when information about terrain type or land cover is known, it can be used in the filtering to improve the accuracy of the resultant DTM. Moreover, data obtained in leaf-off conditions were found more suitable for mapping the terrain surface than data obtained in leaf-on conditions (Raber et al., 2002b).

The objective of this paper is to demonstrate in detail the quality of first pulse derived DTM in boreal forests. In boreal forests, dominant tree species are pine and spruce and the number of pulse hitting the bare ground or the undergrowth is higher than in Central Europe. Impacts of forest cover, as well as the effect of interpolation errors, terrain slope, and 'scanning' angle on first pulse-derived DTM were studied. The knowledge obtained from the study will help in the design of appropriate strategies for data collection and processing in order to minimize these errors and, therefore, improve the accuracy of obtained DTM, especially when object models are of main interest.

2. STUDY AREA AND DATA SETS

2.1 Test Site

Boreal, dense forest almost in natural stage was selected for the study. The Kalkkinen site is located 130 km north of Helsinki. The 2-km-by-0.5-km study area is situated about 110 m above sea level with slopes ranging between 0^o and 66^o, including large-scale variation. About 87% of the test area is covered with forest, consisting of spruce (main species), pine and birch.

2.2 Airborne Laser Scanner Data

A German TopoSys-1 airborne laser scanner was used for data collection in the Kalkkinen area on June 15, 2000 under leaf-on condition. Additionally, the undergrowth was already reasonably well established. Flying altitudes were 400 m and 800 m (a.g.l.) resulting in point densities of 8 to 10 points/m^2 and of 4 to 5 points/m^2, respectively. Both first and last returns were recorded. Technical information on the laser system is given in Hyyppä, J. et al. (2005). Point clouds were transformed into Finnish Coordinate System (YKJ) before any further processing.

2.3 Reference Data

Reference data in the study area were collected in order to test the accuracy of derived DTMs. The measurements were carried out using a Wild T2002 theodolite with Distometer. Before the measurements, the instrument was oriented with known reference points near the test sites so that the measured values would be in the same coordinate system as the transformed laser data.

About 2200 surveyed ground points were collected in October to November 2002 at eight different test plots, with an average size of about 25 m by 30 m each. Six plots including 1474 points covered by one flight line were used in the analyses. Plots were chosen so that they represented different types of forest and terrain. Measured points were distributed evenly inside the plots at a distance of about 2 m from each other. In addition to this, points near the base of trees were also measured and recorded, together with the tree species information. A total of 491 such points were recorded. The random error of the elevation measurements was estimated to be few centimeters, and small systematic shifts between the plots could exist/occur.

3. METHODOLOGY

3.1 Creation of DTM From Laser Data

Laser point clouds were first classified by TerraScan software to separate the ground points from other points. Two different methods were used to create the DTM.

I) The ground points were triangulated using method developed by Axelsson (2000). Triangulated DTMs for both pulse modes were generated for the whole area. These DTMs were used to evaluate the accuracy of DTM using field measurements. DTM from last returns was used for comparison with the DTM from first returns.

II) A raster DTM grid with a 50 cm pixel size was created from classified ground points of first returns by taking the mean value of the ground points within the grid. Missing points in the DTM were afterwards interpolated using Delaunay triangulation and the bilinear interpolation method.

The grid approach was selected since many object models are done with raster data. TIN model was created to compare the difference of grid and TIN models. In theory, optimal results are obtained with TIN. In the following analyses, DTM in grid model, created from first returns was used unless otherwise stated.

3.2 Creation of Canopy Height Model from Laser Data

The canopy height model (CHM) is the difference between the tree-crown surface model and the DTM. The tree-crown surface model was calculated by taking the maximum value of all laser returns within the grid of 50 cm size. Missing points were interpolated using Delaunay triangulation and the bilinear interpolation method.

3.3 Forest Cover Determination

Individual trees were then delineated from the created CHM by segmentation software developed by Arbonaut Ltd, based on the watershed algorithm (Hyyppä et al., 2001). The segments were used to classify the reference points under the tree canopy as tree points (tree) and in the open area between trees as non-tree points (non-tree) in order to evaluate the effect of forest cover.

3.4 Evaluation of the Laser DTM

To evaluate the laser DTM accuracy, the differences between laser-derived elevations and field measurements at the location of reference points were calculated, after the calibration of laser point clouds using reference objects (roads, houses, flat areas with known elevation). In addition to tree-cover effect, the effect of interpolation error, slope, and 'scanning' angle on laser DTMs were also evaluated by statistical analyses. 'Scanning' angle was an approximation of actual scanning angle by assuming that the aircraft flies along a straight path at a constant height.

One advantage with laser techniques is that a reasonable number of laser pulses can penetrate the forest canopy and reach the underlying ground. Penetration rate (relative number of pulses reaching the ground) is affected by stand density, tree species, age and leaf-area index, and particularly by the stand density and closure of the canopy. Canopy cover of 80-90% can result in only 10% of the laser pulse reaching the ground (Cowen et al., 2000), thus leaving a 'hole' in the ground data. The elevations of the 'holes' have to be interpolated from neighboring ground points. Early study (Hodgson et al., 2003) showed that the distance of interpolated points to the nearest laser point influences the accuracy of the interpolated points. In order to test how substantial the influence can be, reference points were divided into two data categories according to how the corresponding DTM points were produced: laser points (LPS) and interpolated points (IPS). LPS have a penetration rate greater than zero and IPS a value of zero. The penetration rate of laser pulses through the tree canopy for each pixel was calculated as follows:

$$penetration = \frac{N_g}{N} \quad (1)$$

where N_g is the number of laser pulse hits on the ground and N is the total number of laser hits respectively within the pixel. For the Kalkkinen DTM, about 88% of pixels were interpolated.

The slope and 'scanning' angle were computed from a DTM derived from laser scanner data and then classified into different classes with 2^o or 5^o intervals depending on the range of the data.

4. RESULTS

4.1 Effect of Using First Return

First, the last and first pulses DTM accuracy was compared. The accuracy of the laser DTM was evaluated by comparing the DTM values with the corresponding reference points obtained by field measurements, Figure 1. Systematic elevation error was calculated as mean height differences (bias, z) between laser DTMs and field measurements, whereas the random error was obtained from standard deviation (std) of the difference. Systematic overestimations of the triangulated DTM were 19 cm and 2 cm for the first and last pulse, respectively, for 400 m data. The corresponding standard deviations were 19 cm and 15 cm, respectively. The systematic shift between the pulse modes was then 17 cm. It should be noticed that the systematic shift could change during the growing seasons due to changes in the undergrowth, see Hyyppä, H. et al. (2005). The corresponding systematic shift at 800 m was 21 cm. Obviously, the flight parameters, such as pulse density and beam size, affect on the shift (see also Hyyppä, H. et al., 2005). The shift in random error was 3 cm for the 800 m data.

Figure 2 shows the corresponding systematic and random errors for all plots separately. Due to the changes in the undergrowth and terrain type, the biases change from 9 cm to about 20 cm.

The upward shift of 10 to 20 cm due to the use of the first pulse mode is not severe when tree heights are typically underestimated by 50 to 150 cm. The less than 5 cm decrease in the random error is negligible for object target models in forest areas.

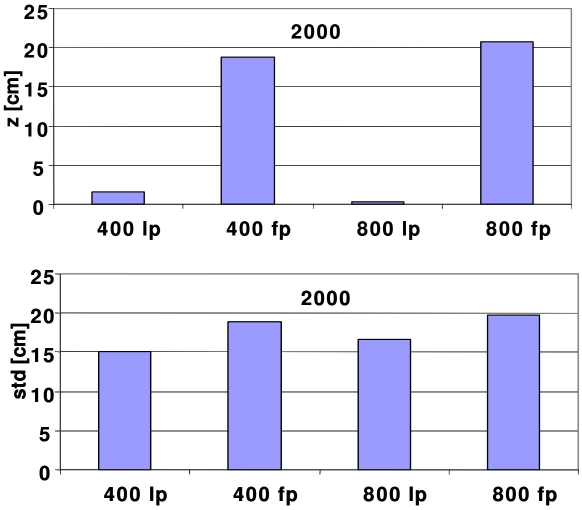

Figure 1. The systematic and random errors between first pulse and last pulse modes, altitudes 400 and 800 m AGL. lp refers to last pulse and fp to first pulse mode.

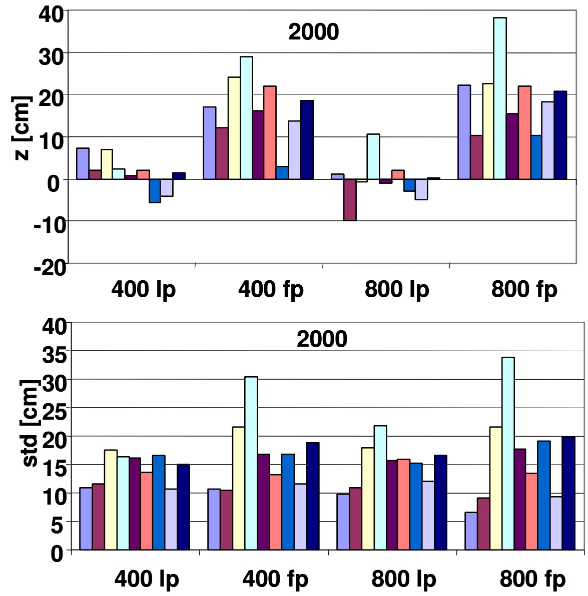

Figure 2. The systematic and random errors between first pulse and last pulse modes, altitude 400 m AGL, for each eight plot separately.

4.2 Interpolation Errors in Grid Model

Systematic and random errors were calculated separately for laser points (LPS) and interpolated points (IPS) to evaluate the interpolation error. A systematic error of 0.17 m was obtained with a random error of 0.18 m for LPS, and a systematic error of 0.21 m with a random error of 0.21 m for IPS, using 400 m first returns. The difference was statistically significant. The elevation of interpolated points was overestimated by 4 cm. The interpolation errors are about the same as those obtained by Hodgson and Bresnahan (2004), which were up to 3.3 cm to any land-cover class.

4.3 Effects of Forest Cover

In order to evaluate the effect of forest cover in grid model on DTM accuracy and to avoid the influence of the interpolation, field measurements were classified as under tree cover (tree) or at open area (non-tree) based on forest cover determination in 3.3. In each class, effects were examined for three data groups consisting of all reference points (All), merely laser points (LPS), and interpolated points (IPS) (Figure 3). In general, there was a 7 cm systematic shift upwards on the DTM under trees, which consisted of 3 cm shift for laser points and 9 cm for interpolated points. The corresponding shifts in random errors were 3, -6 and 5 cm. It should be noted that most of the under tree points are interpolated. The mean distances to the nearest laser points were 0.56 and 1.65 m for non-tree and tree classes. The effect of forest cover for DTM can be further illustrated by the TIN model of the classified ground points in Figure 4. It is clear that forest cover has more impact on first pulse than on last pulse.

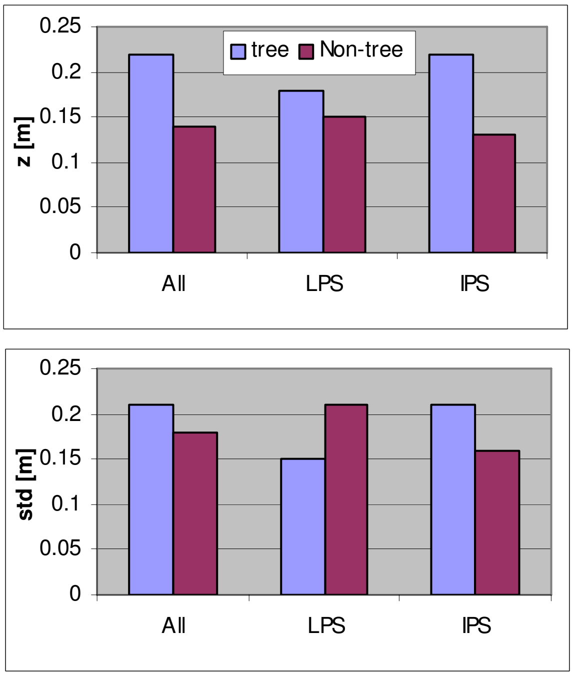

Figure 3. DTM systematic and random errors for tree-covered and open areas.

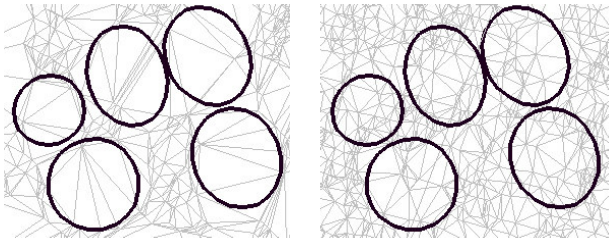

Figure 4. TIN models of the terrain using first (left) and last (right) pulse.

4.4 Effects of Slope

Effects of terrain slopes on laser DTM are shown in Figure 5 for three data categories. Accuracy generally deteriorated when the slope increased to more than 15°. Elevation errors for interpolated points increased substantially for slopes greater than 15° degrees. Results may indicate that interpolation error is the dominant factor influencing the accuracy of laser DTM and as slope increases, interpolation errors also increase.

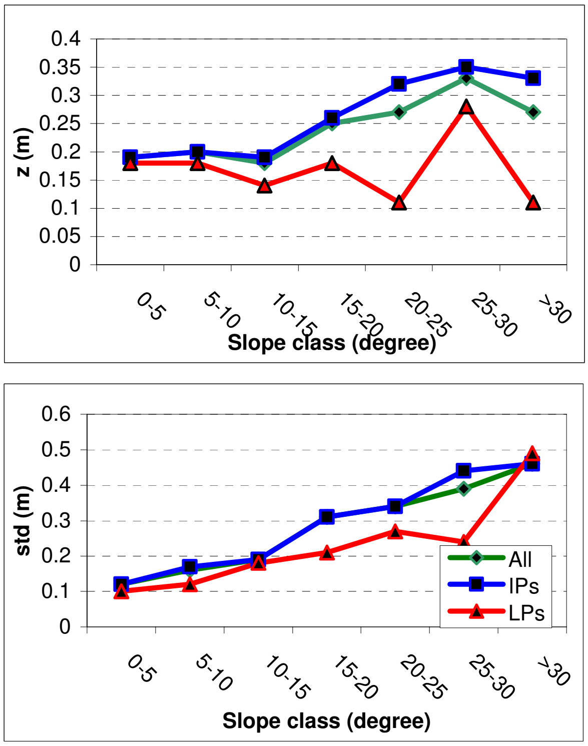

Figure 5. Elevation errors as a function of terrain slope

4.5 Effects of 'Scanning' Angle

Since scanning angle was less than 7°, no systematic trend as a function of scanning angle was observed.

4.6 Effects of Tree Species

Other tree species than the three dominant ones (pine, spruce and birch) were classified as 'others'. Results are summarized in Table 1. The accuracy of laser DTM varied with tree species, and the differences are statistically significant. The best results were obtained for pine and birch with elevation errors of 0.13 m and 0.14 m, respectively and random errors of 0.18 m and 0.17 m. The worst result was obtained for spruce. This suggests that spruce intercepts more of the laser pulses than other tree species, resulting in a lower number of ground points under spruce canopy. Accordingly, the lowest penetration and the greatest mean distance to nearest laser points were observed with spruce canopies. This is not a surprise. In a recent study conducted by Hodgson and Bresnahan (2004), the lowest error was also found for pine.

Tree species	z (m)	std (m)	Penetration	Mean Distance to nearest LPS (pixel)
Pine	0.13	0.18	0.06	2.8
Spruce	0.23	0.22	0.04	3.6
Birch	0.14	0.17	0.04	3.2
Others	0.18	0.17	0.16	3.2

Table 1. Effects of tree species on laser DTM.

4.7 Plot Based Analyses

DTM quality was compared against forest inventory parameters, namely mean tree height and basal area, for six plots. The results are shown in Table 2. DTM accuracy is strongly related to the dominant tree species on the plots and has less degree of correlation with the basal area and height of the plots. The accuracy was lowest for the plots dominated by spruce. The correlation between DTM accuracy and basal area or height for plots with the same dominant tree species needs to be further verified with more data in the future.

z (m)	std (m)	Mean tree height (m)	Basal area (m^2/ha)	Composition (%) pine/spruce /birch/others
0.29	0.22	23.1	29.3	4/66/16/14
0.30	0.31	24.8	28.9	11/78/ 3/ 8
0.19	0.18	18.0	16.2	55/25/13/ 7
0.21	0.13	24.8	33.5	46/36/ 7/11
0.09	0.16	7.2	10.1	30/23/35/12
0.13	0.10	25.2	28.3	5/13/77/ 5

Table 2. Plot based laser DTM analysis.

5. DISCUSSION

In general, the results are consistent with earlier laser scanning DTM studies (e.g. Pfeifer et al., 2001; Vosselman, 2000; Pereira and Janssen, 1999), where typically errors of less than 15 cm have been obtained for relatively flat terrain. The difference is that the results obtained in this study are based on first pulse data, earlier papers are based on last pulse.

Hodgson et al. (2003) reported an RMSE of 93 cm for the LIDAR derived elevations. They suggest that the 15 cm threshold advertised by LIDAR service providers is not obtainable during the growing season over any surface with vegetation cover. In their study, low-density data (1 pulse/11.6 m^2) from high altitude (2400 m) and large scanning angle (resulting in a 1.8 km swath width) were used. All these characteristics are reasons for the lower accuracy obtained.

6. SUMMARY

The study showed that the use of first pulse data in boreal forest zone resulted in comparable random errors as last pulse derived DTM. Even under leaf-on conditions, the random errors were typically less than 20 cm. The major difference in the performance is the small upward shift of the order of 10-20 cm in the first pulse DTM, mainly due to the height of the undergrowth. On object model construction (forest inventory, corridor mapping, flight obstacle mapping, telecommunication planning), typically dealing with canopy height models, 10-20 cm errors are acceptable, since trees grow even up to 1 m per year.

It was shown that using the first pulse for DTM generation, the most significant factors affecting the accuracy of the DTM are tree species, terrain slope and the vegetation cover and density of the point clouds (flight altitude). Accuracy in the area dominated by spruce is worse than in the area with other tree species. Other forest parameters, such as density and height of trees seem to have smaller effect. In general, forest cover caused a loss in terrain details and introduced interpolation errors in DTM. The level of introduced error will clearly be more significant in areas where surface form changes are greater, such as in clusters of vegetation and steep slopes.

This information is useful for optimizing accuracy-versus-costs of DTM acquisition with laser scanners. This study can also be used as an evidence that first pulse derived DTMs can give high accuracy results for boreal forest studies and inventories. It should be a subject of further studies, how much low vegetation, such as bushes etc, affect on the use of the first pulse mode.

7. REFERENCES

Ahokas, E., H. Kaartinen, X. Yu, J. Hyyppä and H. Hyyppä, 2003. Analyzing the effects related to the accuracy of laser scanning for digital elevation and target models. *Proceedings of the 22nd symposium of the European Association of Remote Sensing Laboratories*: In Geoinformation for European wide Integration, 4-6 June 2002, Prague, pp 13-18.

Axelsson, P., 2000. DEM Generation from Laser Scanner Data Using Adaptive TIN Models. *International Archives of Photogrammetry and Remote Sensing*. 16-23 July 2000, Amsterdam (International Society for Photogrammetry and Remote Sensing) Vol. XXXIII(B4), pp 110-117.

Baltsavias, E.P., 1999. Airborne laser scanning: Basic relations and formulas. *ISPRS Journal of Photogrammetry and Remote Sensing*, 54, pp.199-214.

Burman, H., 2000. Adjustment of Laser-scanner data for correction of orientation errors. *International Archives of Photogrammetry and Remote Sensing*, 16-23 July 2000, Amsterdam, (International Society for Photogrammetry and Remote Sensing) XXXIII (B3/1), pp 125-132.

Crombaghs, M.J.E., R. Brügelmann and E.J.de Min, 2000. On the adjustment of overlapping strips of laser altimeter height data. *International Archives of Photogrammetry and Remote Sensing*, 16-23 July 2000, Amsterdam (International Society for Photogrammetry and Remote Sensing), XXXIII(B3/1), pp. 230-237.

Cowen, D.J., J.R. Jensen, C. Hendrix, M.E. Hoagson and S.R. Schill, 2000. A GIS-assisted rail construction econometric model that incorporates LIDAR data. *Photogrammetry Engineering & Remote Sensing*, 66(11), pp.1323-1326.

Huising, E.J. and L.M. Gomes Pereira, 1998. Errors and accuracy estimates of laser data acquired by various laser scanning system for topographic applications. *ISPRS Journal of Photogrammetry and Remote Sensing*, 53, pp. 245-261.

Hodgson, M.E., J.R. Jensen, L. Schmidt, S. Schill and B. Davis, 2003. An evaluation of LIDAR- and IFSAR- derived digital elevation models in leaf-on conditions with USGS Level 1 and Level 2 DEMs. *Remote Sensing of Environment,* 84, pp. 295-308.

Hodgson, M.E. and P. Bresnahan, 2004. Accuracy of airborne lidar-derived elevation: Empirical assessment and error budget. *Photogrammetry Engineering & Remote Sensing*, 70(3), pp. 331-339.

Hyyppä, H., Yu, X., Hyyppä, J., Kaartinen, H., Honkavaara, E. and Rönnholm, P., 2005. Factors affecting the quality of DTM generation in forested areas. Submitted to ISPRS Workshop Laser scanning 2005.

Hyyppä J., U. Pyysalo, H. Hyyppä, H. Haggren and G. Ruppert, 2000. Accuracy of laser scanning for DTM generation in forested areas. *Proceedings of SPIE 4035 Laser Radar Technology and Applications V*, 26-28 April, Orland USA. (International Society for Optical Engineering),

Hyyppä, J., O. Kelle, M. Lehikoinen and M. Inkinen, 2001. A segmentation-based method to retrieve stem volume estimates from 3-dimensional tree height models produced by laser scanner. *IEEE Transactions on Geoscience and Remote Sensing* 39, pp.969-975.

Hyyppä, J., T. Mielonen, H. Hyyppä, M. Maltamo, E. Honkavaara, X. Yu and H. Kaartinen, 2005. Using individual tree crown approach for forest information extraction based on aerial images and laser point clouds. Submitted to ISPRS Workshop Laser Scanning 2005.

Kraus, K. and N. Pfeifer, 1998. Determination of terrain models in wooded areas with airborne laser scanner data. *ISPRS Journal of Photogrammetry & Remote Sensing* 53, pp. 193-203.

Lloyd, C.D. and P.M. Atkinson, 2002. Deriving DSMs from lidar data with kriging. *International Journal of Remote sensing* 23(12), pp. 2519-2524.

Pereira, L.M.G. and L.L.F. Janssen, 1999. Suitability of laser data for DTM generation: a case study in the context of road planning and design, *ISPRS Journal of Photogrammetry & Remote Sensing* 54, pp 244-253.

Petzold B., P. Reiss and W. Stössel, 1999. Laser scanning-surveying and mapping agencies are using a new technique for the derivation of digital terrain models. *ISPRS Journal of Photogrammetry & Remote Sensing* 54, pp. 95-104.

Pfeifer N., P. Stadler and C. Briese, 2001. Derivation of digital terrain models in the SCOP++ environment. *OEEPE Workshop on Airborne Laserscanning and Interferometric SAR for Digital Elevation Models*, 1-3 March, Stockholm, (Royal Institute of Technology), unpaginated.

Raber, G.T., J.R. Jensen, S.R. Schill and K. Schuckman, 2002a. Creation of digital terrain models using an adaptive Lidar vegetation point removal process. *Photogrammetry Engineering & Remote Sensing* 68(12), pp 1307-1315.

Raber, G.T., M.E. Hodgson, J.R. Jensen, J.A. Tullis, G. Thompson, B. Davis and K. Schuckman, 2002b. Comparison of LIDAR data collected leaf-on vs. leaf-off for the creation of digital elevation models, *Proceedings of the ASPRS 2002 Annual Convention*, 19-26, April, Washington, D.C. (American Society of Photogrammetry and Remote Sensing) unpaginated CD-ROM.

Roggero, M., 2001. Dense DTM from laser scanner data. *Proceedings of OEEPE workshop on Airborne Laserscanning and Interferometric SAR for detailed Digital Elevation Models.* 1-3 March, Sweden, (Royal Institute of Technology), unpaginated.

Ruppert, G.S., A. Wimmer, R. Beichel and M. Ziegler, 2000. Adaptive Multiresolutional Algorithm for High-precision Forest Floor DTM Generation. *Proceedings of SPIE. 4035 Laser Radar Technology and Applications V*, 26-28 April , Orland USA. (International Society for Optical Engineering).

Schenk, T., 2001. Modelling and analysing systematic errors in airborne laser scanner. Technical Notes in Photogrammetry, No. 19, Dept. of Civil and Environmental Eng., OSU, 42p.

Sithole, G., Vosselman, G., 2004. Experimental comparison of filter algorithms for bare-Earth extraction from airborne laser scanning point clouds. *ISPRS Journal of Photogrammetry and Remote Sensing* 59, pp. 85-101.

Volsseman, G., 2000. Slope Based Filtering of Laser Altimetry Data. *International Archives of Photogrammetry and Remote Sensing*. 16-23 July 2000, Amsterdam (International Society for Photogrammetry and Remote Sensing) Vol. XXXIII (B3). pp 935-942

Vosselman, G. and H.G. Maas, 2001. Adjustment and filtering of raw laser altimetry data. *Proceedings of OEEPE workshop on Airborne Laserscanning and Interferometric SAR for detailed Digital Elevation Models*. 1-3 March, Sweden, (Royal Institute of Technology), unpaginated.

Wehr, A. and U. Lohr, 1999. Airborne laser scanning – an introduction and overview. *ISPRS Journal of Photogrammetry and Remote Sensing* 54, pp. 68-82.

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