Quality of laser scanning

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ABSTRACT: This paper describes quality of airborne laser scanning concerning analysis methods, digital terrain model quality, quality of building extraction and possibilities for laser scanning based change detection. Analysis methods include the use of portable brightness targets for intensity calibration, and co-registration of laser points with image data using an interactive orientation method. A quality of DTMs derived both from first pulse and last pulse laser data in boreal forests will be depicted. In the building extraction part accuracies obtained from photogrammetry and laser scanning was compared. Altogether 11 European participants created 3D city models in the EuroSDR project. Finally, change detection in the forests (tree growth) and urban areas (buildings) will be dealt with.

1 INTRODUCTION

Airborne laser ranging/profiling developed rapidly in early and middle 1970's, especially in North America, with experiments for bathymetric and hydrographic applications. In the late 1980's the use of GPS made accurate range measurements on a larger scale possible. In early 1990's, profiler where gradually replaced by scanners, and GPS was combined with INS, enabling the collection of 3D coordinates for the reflected points. First, the airborne laser scanning (ALS) systems had to collect separately first and last pulse. Today all systems are capable to record simultaneously at least the first and last pulse, and some are even capable to record multiple pulses, continuous waveforms and aerial photographs in parallel. Pulse rates up to 100 kHz have been demonstrated.

The quality of products 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. point density, first/last pulse, flight height, scan angle), as well as 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. 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. The errors created during processing of the data depend highly on applied algorithm and terrain type. In order to create accurate DSMs or DTMs from laser scanning data, filtering of both blunders and undesired objects is required (Axelsson, 2000; Hyyppä et al., 2000; Kraus et al., 1998; Ruppert et al., 2000; Vosselman, 2000).

Finnish Geodetic Institute (FGI), Helsinki University of Technology and Terrasolid Ltd conducted a laser scanning quality project during 2002-2004. This paper and the presentation summarize the major findings found in the project on the following areas: 1) quality analysis methods, 2) DTM quality, 3) building extraction quality, 4) possibilities with laser-based change detection. Building extraction results are based on FGI-coordinated EuroSDR Building Extraction project with 11 participants from Europe.

2 DEVELOPED QUALITY ANALYSIS METHODS

2.1 *Intensity calibration*

In Kaasalainen et al. (2005) systematic laboratory measurements of laser backscatter intensity were presented for brightness calibration targets and a calibration scheme for airborne laser scanner intensity data was proposed. Thus far, the use of these data has been partly hampered by the variability of the intensity with time, and no test fields have been available for airborne reflectance calibration. Portable brightness targets (tarps), with nominal reflectance from 5% to 70%, were manufactured, and, based on these measurements, found suitable for lidar reflectance standards.

The materials for portable targets were strong enough to endure hard field conditions when deployed occasionally over several years. The brightness targets used in this experiment were manufactured by Suojasauma Oy in Kuopio, Finland in 2000. The size of one target is 5 by 5 meters. The tarps are portable and can be arranged in a straight line in a test field and attached together with finger joints and composite poles (the number and combination of targets can thus be varied depending on the available space). Each tarp can be transported in a carrying bag with mounting poles, pulley tackles, and steel pegs. The tarps are stored in these bags in dry room conditions. Eight targets with nominal reflectance of 5%, 10%, 20%, 25%, 30%, 45%, 50%, and 70% were manufactured, and their reflectance optimized at a wavelength range of 400 to 800 nm. As the reflectance values provided by the manufacturer were approximate, the demand for their more accurate laboratory calibration was crucially needed for their use in remote intensity calibration. The targets are made of polyester 1100 dtex with polyvinyl chloride (pvc) coating. The weight of the fabric is 600g/m^2. They were coated with titanium dioxide and carbon black paint mixing pigments. Delustring agent was added to the paint to get a mat surface and to decrease the non-lambertian reflectance effects. A mat surface does have its disadvantages; dirt attaches itself into the surface more easily in outdoor campaigns, and cleaning is more difficult. Because of their relatively smooth surfaces and similarity in surface structure, the test targets are well suited for the study of surface albedo effects on backscattering.

2.2 *Method to co-register laser point clouds with image data or other point cloud.*

A method using interactive orientation for point cloud data was developed. The advantages of interactive orientation are achieved, if there exists random variation in the 3D data, e.g. in the laser point cloud data. The human intelligence can perceive the entity and filter out possible random inaccuracies during the registration of images and reference data. The interactive orientation is also suitable for traditional orientation tasks, when accurate 3D reference data, e.g. points or lines, exists. The method is depicted in detail in Rönnholm et al. (2003).

2.3 *Repeatability of laser flight lines*

The repeatability of the laser measurements was investigated in Rönnholm (2004) using five almost completely overlapping laser strips measured with TopoSys Falcon. The differences between strips were measured in thirty-nine small test sites from the test area covering 1500x100 meters. One strip was selected as a reference strip and four others were compared to that one. In each test site, the entity of two laser point clouds was oriented directly to the same coordinate system using interactive orientation method. The repeatability of elevations, according the test sites, was excellent. The largest systematic bias was -0.014 m. With other strips no significant systematic bias was found. In addition, the standard deviation was 0.011, or less, for every comparison confirming the homogeneity of elevation measurements. Even maximum differences were only 0.02-0.04 m depending on the strip. The flight direction did not make any noticeable difference to repeatability of elevations.

As expected, the planimetric repeatability was not as good as with heights. However, the maximum systematic biases of 0.064 meters in along-track direction and -0.019 meters in across-track direction are still quite reasonable. The bias and deviation in across-track direction may have been underestimated, because there were less suitable tie features for that direction and because of the properties of TopoSys Falcon scanning footprint. The flight direction was the most distinguishable reason of systematic planimetric errors. When the strips, flown from the same direction, are compared among each other, the maximum bias was only -0.014 m in the along-track direction and 0.006 m in across-track direction.

Some non-systematic errors were found within the laser strips. Typically, these errors were accumulated making wave-like pattern, leading to the conclusions the main source of these errors is inaccuracies of GPS and INS. Against the assumptions, there were no clear differences, whether the test area located in the middle or in the either side of the strip. Over all, the system calibration of TopoSys Falcon seems to be successed well.

The laser strips are not completely homogenous. The repeatability in altitudes is excellent, but the planimetric variations slightly reduce the usability of this information. Therefore, the main concern when improving the quality of laser data is, how to get the planimetric accuracy into as uniform quality as possible.

3 DTM QUALITY

The test site was placed 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^{o} and 66^{o}, with 87 % of forest cover, with species such as spruce, pine and birch, was collected with Toposys-1 and Toposys Falcon in 1998, 2000, and 2003. In all campaigns, the 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 the Toposys-1 and Falcon was the possibility to record first and last pulse simultaneously in the version Falcon. Since the measurements were recorded at various time of the season, i.e. May 14 th 2003 (leaf-off), June 14 th 2000 (leaf-on, low development of undergrowth), and August 31st 1998 (leaf-on, high undergrowth), it was possible to estimate the effect of leaves and undergrowth at boreal forest zone. That was done by using the high pulse density point cloud (8-10 pulses per m^2) obtained from 400 m (AGL) flight altitude in each acquisition. The effect of the flight altitude was possible to be studied, since in 2003 the flight altitudes of 400, 800 and 1500 m (AGL) were used providing nominal pulse densities of 8-10, 4-5 and 2-3 pulses per m^2.

3.1 *Quality of first pulse derive DTMs in forested terrain*

In Yu et al. (2005) quality of first pulse derived DTM in boreal forests was depicted. 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 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 forest height, 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 evidence that first pulse derived DTMs can give high accuracy results in boreal forest zone. It should be a subject of further studies, how much low vegetation, such as bushes etc, would affect on the use of the first pulse mode.

3.2 *Quality of last pulse derive DTMs in forested terrain*

In the paper by Hyyppä et al. (2005) 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 were discussed on the DTM accuracy.

The following conclusions could be drawn with high density data:

- At boreal forest zone, the random errors of less than 20 cm can be obtained in most conditions for non-steep terrain.
- The increase of flight altitude from 400 m 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 similar 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 determine this systematic behaviour. Additionally, the systematic shifts between last and first pulse are significant.
- The difference of DTMs derived at optimum and non-optimal season conditions has typically a difference less than 5 cm with high density data (not relevant for most applications and users). 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 detail.
- The random error increases with increasing terrain slope.
- The effect of forest cover is higher when moving closer to the trunk. Near trunks the systematic shift is 3-6 cm.
- The results are site dependent, i.e. the obtained accuracy varies as function of site conditions (slopes, undergrowth, forest cover).

4 BUILDING EXTRACTION QUALITY

In Kaartinen et al. (2005) accuracies obtained with photogrammetry and laser scanning were compared in building extraction. The objective of the EuroSDR Building Extraction comparison was to evaluate the quality, accuracy, feasibility and economical aspects of semi-automatic building extraction based on photogrammetric techniques with the emphasis on commercial and/or operative systems, semi-automatic and automatic building extraction techniques based on high density laser scanner data and semi-automatic and automatic building extraction techniques based on integration of laser scanner data and aerial images. The project consists of three test sites by Finnish Geodetic Institute (FGI), namely Senaatti, Hermanni and Espoonlahti and one test site by Institut Geographique National (IGN), namely Amiens. For each test site following data was provided to the partners: aerial images, camera calibration and image orientation information, ground control point coordinates and jpg images of point locations (not for Amiens), laser scan data and cadastral map vectors of selected buildings. Participants were requested to create the vectors of the 3D city models. 3D-models were obtained from 11 participants.

In general photogrammetric methods are more accurate in determining building outline. The inter quartile range (IQR) value of photogrammetric methods ranged taking into account all test sites from 14 to 36 cm (average 21 cm, median 22 cm and std 7.2 cm of IQR values). The corresponding values for aerial image assisted laser scanning ranged from 20 to 76 cm (mean 44 cm, median 46 cm, std 18.5 cm). Laser scanning based building outline errors ranged from 20 to 150 cm (mean 66 cm, median 60 cm, std 33.2 cm).

Point density, shadowing of trees and complexity of the structure were the major reason for site wise variation of the laser scanner based results. Lowest accuracy was obtained with lowest pulse density (Senaatti). Also in Amiens, the complexity deteriorated the performance. It was almost impossible to reveal the transition from one house to another using DSM data in Amiens. The low amount of trees, simple building structure and relatively high pulse density resulted in the highest accuracy in Hermanni test site.

In building length determination, laser based methods are not as accurate as photogrammetric methods, as can be expected from the above. Deviations of the photogrammetrically derived lengths varied from 14 to 51 cm (RMSE, mean 26 cm, median 22 cm, std 12.6 cm). Deviations of lengths obtained with aerial image assisted laser scanning varied from 19 to 108 cm (mean 59.4 cm, median 57 cm, std 31.2 cm). Deviations of the laser scanning based lengths varied from 13 to 292 cm (mean 93 cm, median 84.5 cm, std 609 cm). With laser scanning the complexity of the buildings was the major cause for site wise variation rather than the point density.

Laser scanning is at its best in deriving building heights, extracting planar roof faces and ridges of the roof. The IQR value for the laser scanning height determination ranged from 4 to 153 cm (mean 32 cm, median 22 cm, std 31.5 cm). One fully automatic method caused high errors modifying the mean value. Laser scanning assisted by aerial images resulted in IQR values from 9 to 34 cm (mean 18 cm, median 16.5 cm, std 8.5 cm). Photogrammetric height determination ranged from 14 to 54 cm (mean 33 cm, median 35 cm, std 18 cm). Height determination accuracy followed exactly the laser scanning point density. With high density data at Espoonlahti, all participants were capable to provide average height with less than 20 cm IQR value.

Roof inclination determination was more accurate when using laser data than photogrammetry, but there exists large variation in quality due to methods and test sites (i.e. complex buildings). The RMSE using laser scanning for roof inclination varied from 0.3 to 9 degrees (mean 2.7 degrees, median 0.85 degrees, std 4.4 degrees). The corresponding values for aerial image assisted laser scanning ranged from 0.6 to 2.3 degrees (mean 1.3 degrees, median 1.1 degrees, std 0.6 degrees) and for photogrammetry range from 1.0 to 17.9 degrees (mean 5.2 degrees, median 3.2 degrees, std 6.3 degrees). In Senaatti and Amiens, the roof inclinations are steep and roofs short, so even small errors in target height determination lead to large errors in inclination angle. Test site Hermanni is relatively easy for both methods, in Hermanni the accuracy of roof inclination determination was about 2.5 degrees for photogrammetric methods and about 1 degree (RMSE) for laser based methods by the degree of automation. The target height accuracy seems to be almost independent of the degree of automation. It is needed to further study the obtained accuracy with each method in order to be able to develop new, better algorithms, especially for laser scanning.

5 POSSIBILITIES WITH CHANGE DETECTION

5.1 *Tree Height Growth Determination*

It is well known that characteristics of individual trees, such as tree height, biomass and crown area, can be derived from airborne laser scanning (ALS) and that heights for individual trees can be obtained with an accuracy of 0.5 to 1.5 m. However, the ability to measure the growth of individual trees using ALS has not been documented. Yu et al. (2005) reported multi-temporal laser surveys conducted in a boreal forest zone suggesting that the height growth for individual trees can be measured with an accuracy better than 0.5 m. Methods to automatically extract height growth of tree crowns are presented. It is expected that similar methods are feasible for reference measurements in studies analyzing global forest changes and the carbon sink, in national forest inventories, and in describing the effects of global warming on forest growth.

The coefficient of determination (0.66) between acquisitions in 2003 and 1998 indicates that it is possible to measure the growth of an individual tree. RMSE of individual growth was approximately 45 cm and the bias was 10 cm, indicating an overestimation of the growth by the laser. The bias of the growth between acquisitions in 2000 and 1998 was 0 cm and between acquisitions in 2003 and 2000 was 11 cm. The reason for the biases is most likely to be changes in the sensitivity of the instruments. It seems that the Toposys Falcon is more sensitive than its predecessor Toposys-1. The measurement in early season did not affect on pine trees selected for the study.

The standard deviation of the growth between acquisitions in 2000 and 1998 was 46 cm and between acquisitions in 2003 and 2000 was 38 cm. Most probably the errors related to airborne laser scanning are decreasing as the ALS technology is improving. It is expected that improvements in GPS and IMU technology have reduced the planimetric errors troubling the tree-to-tree matching between data sets.

5.2 *Automatic change detection for map updating*

To keep digital map databases as up-to-date as possible, efficient methods for the data acquisition and updating process are needed. One important and frequently changing class of objects is buildings. The goal of our study (Matikainen et al., 2003, 2004) was to develop an automatic change detection method for updating of building maps. The method was based on laser scanner, aerial image and map data. The idea of the method was to produce a preliminary updated building map that could then be used as a starting point for further steps of map updating. These further steps could be manual, semi-automatic or fully automatic. Laser scanner data were selected as the primary source of data because they have proved to be promising for building extraction and modelling (see e.g. Haala and Brenner, 1999; Maas and Vosselman, 1999; Morgan and Tempfli, 2000; Vögtle and Steinle, 2000). The height information facilitates building detection and in further steps allows 3D modelling.

The method was developed and tested by using two study areas near Helsinki: Otaniemi and Espoonlahti. The size of both study areas was about 2 km^2. From the Otaniemi area, TopEye laser scanner data (point density about 2-3 points per m^2) were available. In Espoonlahti, TopoSys laser scanner data (point density about 10 points per m^2) and an aerial ortho image were used. The change detection method was based on two basic steps: building detection and actual change detection. Buildings were first detected by segmenting a digital surface model (DSM) derived from laser scanner data and classifying the segments as buildings, trees and ground surface. Height and intensity information from laser scanning, aerial image data, shape and size of the segments and neighbourhood information were used in classification (slightly different procedures were used in the two study areas). Detected buildings were then compared with an old building map and classified as new, enlarged and old buildings. Similarly, buildings of the old map were compared with the building detection result and classified as detected, partly detected and not detected. The comparison was based on overlap percentages and threshold values. eCognition (Definiens Imaging, 2005), TerraScan (Terrasolid, 2005) and Matlab (The MathWorks, 2005) software were used in the study.

Compared with up-to-date reference maps, 80% of all buildings and 91% of buildings larger than 200 m^2 were correctly detected in the building detection stage in the Otaniemi study area. In the Espoonlahti area, the detection percentages were 88% for all buildings and 98% for buildings larger than 200 m^2. According to visual evaluation, promising results were also obtained in change detection between old building maps and the building detection results, especially in detecting new buildings. The results of the study suggest that automatic building detection and change detection is possible and could produce useful results for map updating. Further research is needed to improve the segmentation stage to better distinguish buildings from trees and to develop the change detection stage.

6 CONCLUSIONS

Quality issues have been examined on different areas during the laser scanning quality project. Detailed conclusions for chapters 2 to 5 can be found in corresponding referenced publications of the authors of this paper. The accuracy of airborne laser scanner height measurements is nowadays at a level in which one has to be very careful to get reference data/measurements that are good enough for comparison purposes. Planimetric accuracy instead has its deficiencies. Improving GPS/IMU technology will reduce errors in position and orientation. Increasing pulse rates and low altitude flying make it possible to get dense laser point data sets that are even more useful for forest and urban 3D applications.

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