ACCURACY OF 3D CITY MODELS: EuroSDR comparison

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ABSTRACT:

The paper focuses on comparing accuracies obtained with photogrammetry and laser scanning in building extraction and partly compares results obtained with various methods. 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 (hybrid technique). 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 scanner data and cadastral map vectors of selected buildings. Participants were requested to create the vectors of 3D city models. 3D-models were obtained from 11 participants. Paper confirms with experiments that laser scanning is more suitable in deriving building heights, extracting planar roof faces and ridges of the roof whereas the photogrammetry and aerial images are more suitable in building outline and length determination. CyberCity, Stuttgart and TerraScan (performed by ICC) solutions provided the highest accuracy. There seemed to be a higher variation in the quality of other models depending on test site or remotely sensed information.

1. INTRODUCTION

3D geographical information systems suitable for various applications such as urban planning, visualization, environmental studies and simulation (pollution, noise), tourism, facility management, telecommunication network planning, 3D cadastre and vehicle/pedestrian navigation are of increasing importance in urban areas. Semi-automatic and automatic methods in photogrammetric and laser scanning techniques aim at reducing the costs of 3D models with reasonable level of detail. Due to the complexity of the full automation in photogrammetry, the majority of photogrammetric development work has focussed on semi-automatic systems, in which e.g. recognition and interpretation tasks are performed by the human operator, whereas modelling and precise measurement is supported by automation. In some of the systems, the measurements are still done manually but the editing process of the collected points is partly automated. In addition to photogrammetric techniques relying on aerial images, the generation of 3D building models from laser scanning-derived point clouds are becoming an attractive alternative. This development has been triggered by the sensor technology allowing dense point clouds. Also, the integration of laser point clouds as well as aerial photos provides new technological solutions. A short summary of the state of art dealing with building extraction methods can be obtained from Baltsavias (2004), Brenner (2001), Grün (1997), Gülch (2000), Mayer (1999), Maas and Vosselman (1999) and Paparoditis et al. (1998).

The objective of the *Building Extraction* project of EuroSDR Commission III was to evaluate the quality, accuracy, feasibility and economical aspects of

1. Semi-automatic building extraction based on photogrammetric techniques with the emphasis on commercial and/or operative systems
2. Semi-automatic and automatic building extraction techniques based on high density laser scanner data

3. Semi-automatic and automatic building extraction techniques based on integration of laser scanner data and aerial images, later on called hybrid techniques.

This paper reports the results obtained in the comparison.

2. MATERIAL

2.1 Test sites

The paper reports results from three test sites by Finnish Geodetic Institute (FGI), namely Senaatti, Hermanni and Espoonlahti, and Amiens from France. Senaatti includes the area around the Senate Square in Helsinki main city centre, three to six storey houses and Lutheran Cathedral built mainly in the 19th century. It can be considered as a typical European city centre. Hermanni is a residential area with few trees about 3 km of the main city centre with four to six storey block of flats built mainly in the 1950's. A third test site, Espoonlahti, is located in Espoo, about 15 km west of Helsinki with high variability in buildings and DTM and surrounded by a large number of trees. Amiens is a complex area, where most of the buildings are of the same height. The focus of the paper deals with test sites Senaatti, Hermanni and Espoonlahti, therefore more details of them are given below. Concerning details of all the test sites, the reader is referred to Kaartinen et al. (2005).

2.2 Aerial images and laser scanner data

For each test site the following data was provided to the partners:

- aerial images (stereo pair)
- camera calibration and image orientation information
- ground control point coordinates and jpg images of point locations
- laser scanner data
- cadastral map vectors of selected buildings

Table 1. Applied Aerial Images.

	Espoonlahti	Hermanni	Senaatti
Date	26. June 2003	4. May 2001	24. April 2002
Camera	RC-30	RC-30	RC-30
Lens	15/4 UAG-S, no 13355	15/4 UAG-S, no 13260	15/4 UAG-S, no 13260
Calib. date	22. Nov. 2002	18. Jan. 2000	14. April 2002
Altit., scale	860 m, 1:5300	670 m, 1:4000	660 m, 1:4000
Pixel size	14 microns	15 microns	14 microns

The test sites were flown with different laser scanners (TopEye, TopoSys-I, TopoSys-II) and with different pulse densities (from 1.6 to about 20 pulses per m^2).

Table 2. Applied Laser Scanner Data.

	Espoonlahti	Hermanni	Senaatti
Acquisition	14. May 2003	June 2002	14. June 2000
Scanner	TopoSys II	TopEye	TopoSys I
Flight altitude	400 m	200 m	800 m
PRF	83 000 Hz	7 000 Hz	83 000 Hz
Scann. angles	± 7.15 °	± 20 °	± 7.1 °
Point density	10-20 per m^2	7-9 per m^2	1.6 per m^2
Swath width	100 m	Ab. 130 m	Ab. 200m
Mode	First pulse	2 pulses	First Pulse

2.3 Requested task

Participants were requested to create the vectors of the 3D city models using the given material. Participants were allowed to use any method and data combination.

2.4 Reference data

Reference data was collected in November and December 2003 using a Trimble 5602 DR200+ tacheometer. Measured targets include corners of walls, roofs, chimneys and equivalent constructions as well as ground points next to building corners. Altogether about 980 points were measured in Espoonlahti, 400 in Hermanni and 200 in Senaatti. Known points were used to orientate the tacheometer to the coordinate system of the test site.

On all three test sites, FGI repeated observations to same targets from different station set-ups to control the uniformity and accuracy of the reference measurements. The differences in these repeated measurements (with the worst case scenario) were on the average 4.7 cm in plane (max 8.3 cm) and 1.2 cm in height (max 3.5 cm) on altogether 19 control observations.

2.5 Obtained 3D models

3D models were obtained from 11 participants. Table 3 summarizes the data use and the degree of automation.

Table 3. Summary of used data and level of automation for building extraction.

Participant	Used data			Level of automation
	Laser data	Aerial images	Ground plan	
Cybercity		100		low
Hamburg		100		low
Stuttgart		100		low-high
IGN	50	50		medium
ICC laser+aerial	80	20		low
ICC laser	100			low
Nebel+Partner	90	10		high
FOI	100			high
FOI outlines	100		X	high
C+B Technik	100		X	high
Delft	100		X	medium
Aalborg	100		X	high
Dresden	100		X	high

3. METHODOLOGY

3.1 Methods used by the participants

The methods used by the participants are depicted in more detail in Kaartinen et al. (2005).

The advanced model of the **University of Aalborg** applied the adjustment to all points within the building outline and used the weighting of each point to separate the points not belonging to a roof plane. When one roof plane was found, all the points belonging to this roof plane were removed from the point cloud and the process continued interactively.

CyberCity (see e.g. Grün and Wang, 1999) used Visual Star (a digital photogrammetric workstation), CC-Modeler™ and CCEdit for improving the geometry of the building model

(CAD system for 3D city models) and to export the data into the DXF format.

C+B Technik used an in-house developed (by Dr. Wild) software. First a triangle net is created from the laser scanner data. Triangles are combined to surfaces and triangle sides are classified as edge lines. The resulting surfaces, edges and corners are analysed and edited to achieve the typical building objects. The extraction of buildings from laser scanner data is split into an automatic computation phase and into an interactive check and editing phase.

TU Delft used their own software and methods to extract buildings using laser data and ground plans (see Vosselman and Dijkman, 2001, Vosselman and Süveg, 2001).

TU Dresden method (Hofmann, 2004) used point clouds obtained by a pre-segmentation of airborne laser scanner data. It is a plane-based approach that presumes that buildings are characterized by planes. It utilizes a TIN-structure that is calculated into the point cloud. The method only uses point clouds of the ALS data that contain one building.

FOI used their own fully automatic software and methods to extract buildings using laser data with or without given ground plan.

Hamburg University of Applied Sciences used a digital photogrammetric workstation DPW770 using SocetSet from BAE Systems / Leica Geosystems. Based on these measurements the building was modelled. Complex features were broken down into simpler components, which were later combined in AutoCAD. Finally, the measured data was transferred to AutoCAD 2000 for the correction of some measurements and for modelling of the complex buildings.

ICC used TerraScan, TerraPhoto and TerraModeler software by Terrasolid to extract buildings using laser scanner data with and without aerial images.

IGN used calibrated aerial images and laser DSM. They created a pseudo-cadastral map manually using aerial images.

Nebel + Partner used TerraScan software by Terrasolid to extract buildings using laser scanner data. Aerial images were not used for measurements, only image crops were used as superimposed images for a better visual interpretation of the laser point clouds during the measurement of the roofs.

Stuttgart University of Applied Sciences used inJECT1.9 software to semi-automatically extract buildings using aerial images, camera calibration and exterior orientation information. For a description of the used automated tools see (Gülch and Müller, 2001). The general workflow included derivation of image pyramids with MATCH-B software, import of given exterior orientation data into OrthoMaster, automatic interior orientation in OrthoMaster1.4, automatic derivation of MATCH-AT project file, direct import in inJECT1.9 and measurement of buildings without stereo-viewing by a diploma student.

3.2 Analysis using reference points

Reference points were used to analyse the accuracy of the location (single point measurement), length (distance between two points) and roof inclination (slope between two points) of the modelled buildings. Single points were analysed separately for planimetric and height errors.

Mean squared error (abbreviated to MSE), was calculated.

$$MSE = \sum_{i=1}^{n} (e_{1i} - e_{2i})^2 / (n-1) \tag{1}$$

where e_{1i} is the result obtained with the described retrieved model, e_{2i} is the corresponding reference measured value, and n is the number of samples. MSE was divided into systematic and random error (standard error). Additionally, minimum, maximum, medium, and interquartile range (IQR) values were calculated. Interquartile range (IQR) values represent the range between the 25th and 75th quartiles.

$$IQR = p_{75th} - p_{25th} \tag{2}$$

where p_{75th} is the value at 75th quartile and p_{25th} is the value at 25th quartile. For example, if the IQR is 20 cm and median value is 0, 50% of the errors are within ±10 cm. IQR is mainly used as the quality measure of the models in this paper. IQR is not sensitive to large deviations as standard deviation/error. In Kaartinen et al. (2005) the results are given with several quality indicators in order to give a better view of the quality of all models.

4. RESULTS

When comparing the results, it must be stated that not only the analysed methods differ but also the level of experience of operators and the completeness of used procedures differ between participants. Laser scanning methods in universities are merely technology demonstrators rather than final products.

4.1 Accuracy of building outlines and length determination

In general photogrammetric methods are more accurate in determining building outlines, Figure 1. The 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 obtained). The corresponding values for hybrid techniques ranged from 20 and 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).

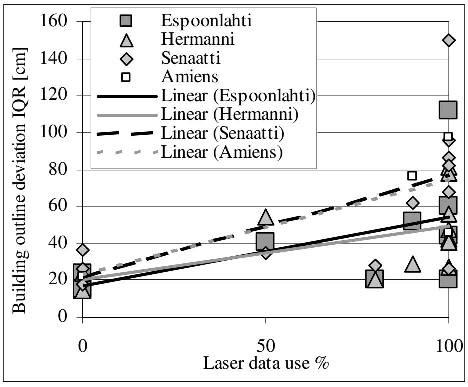

Figure 1. Building outline deviation as a function of laser data use. Laser data use of 0% refers to photogrammetric methods, 100 % to fully laser scanning based techniques and intermediate values to hybrid techniques.

Point density, shadowing of trees and the complexity of the structure were the major reasons for site wise variation of the laser scanner based results. The lowest accuracy was obtained with the 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 the Hermanni test site. The effect of the point density on the achieved average accuracy (planimetric and height errors)is depicted in Figure 2.

In building length determination (Figure 3), laser based methods are not as accurate as photogrammetric methods, as can be expected from the above. Errors in the photogrammetrically derived lengths varied from 14 to 51 cm (RMSE, mean 26 cm, median 22 cm, std 12.6 cm). Lengths obtained with hybrid techniques varied from 19 to 108 cm (mean 59.4 cm, median 57 cm, std 31.2 cm). The laser scanning based lengths varied from 13 to 292 cm (mean 93 cm, median 84.5 cm, std 60.9 cm). With laser scanning the complexity of the buildings was the major cause for site wise variation rather than the point density.

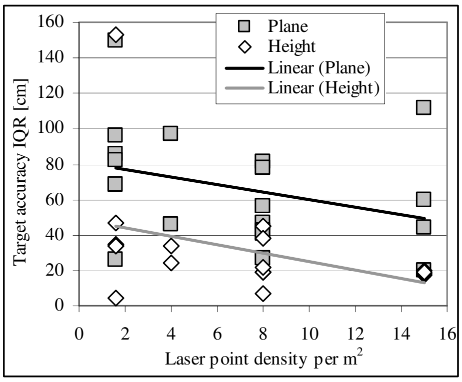

Figure 2. Average accuracy versus laser point density.

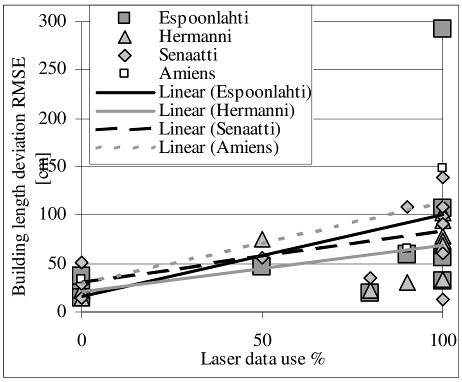

Figure 3. Building length deviation. See the laser data use % description from Figure 1.

4.2 Elevation and roof inclination accuracy

Laser scanning is at its best in deriving building heights (Figure 4), 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. Hybrid techniques resulted in IQR values from 9 to 34 cm (mean 18 cm, median 16.5 cm, std 8.5 cm). Error in 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 in Espoonlahti, all participants provided average height with accuracy better than 20 cm IQR value.

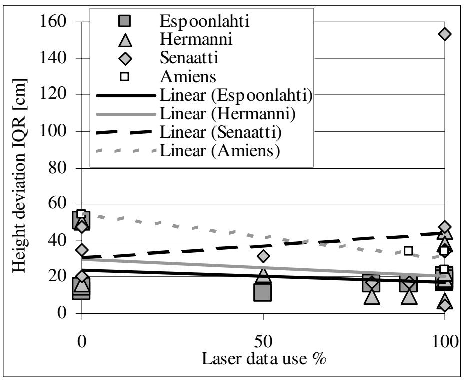

Figure 4. Target height deviation.

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 hybrid techniques ranged from 0.6 and 2.3 degrees (mean 1.3 degrees, median 1.1 degrees, std 0.6 degrees) and for photogrammetry ranged 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 are short, so even small errors in target height determination lead to large errors in inclination angles. 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 degrees (RMSE) for laser based methods.

4.3 Degree of automation and elaborateness

The degree of automation varied significantly among the participants in this test. In general, the laser data allow higher automation in the models. Editing of the complex building models slows down the process. Even though some laser models are relatively automatic, the processes are still under development. In general the planimetric accuracy is affected by the degree of automation (and method, Figure 5); while the accuracy of low automation methods is about 20-30 cm, and the accuracy of high automation methods it is about 60-100 cm (IQR). The target height accuracy seems to be almost independent of the degree of automation, Figure 6. The degree of automation was estimated as a value from 0 to 10 based on the workflow charts and the procedure descriptions provided by participants.

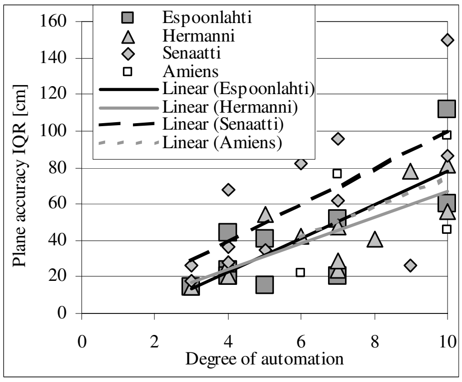

Figure 5. Obtained planimetric accuracy as a function of automation.

In general the methods using aerial images are capable of producing more details using interactive processes, but only some participants modelled more detailed structures such as chimneys and ventilation equipment on roofs.

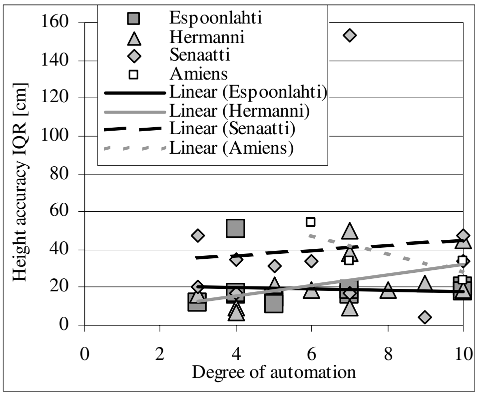

Figure 6. Obtained height accuracy as a function of automation.

4.4 Difference of various models

Figure 7 shows the difference of various models with respect to elevation and planimetric errors for single point targets. The errors are given separately for north-south and east-west directions due to the different point spacing in along and cross track directions of TopoSys systems.

CyberCity had a good quality in all three Finnish test sites. However, the measurements in CyberCity are done manually from stereoscopic images. The quality improved when image quality was better, but in general the accuracy variation within the test sites was low. The Hamburg and Stuttgart models were affected more by the site and site wise data characteristics. Since the test site Hermanni was relatively ease, the Stuttgart model used high automation in Hermanni resulting in decreased performance. With the most difficult test site Espoonlahti, the Stuttgart model was as good as CyberCity model. The Hamburg model showed lower performance than these two other photogrammetric techniques even thought it was based on a more standard photogrammetric process.

Hybrid techniques using the TerraScan (see ICC laser+aerial) showed a quality almost comparable to CyberCity and Stuttgart. The same method (i.e. TerraScan) used by Nebel and Partner showed lower accuracy, which can be explained by the lower amount of time spent and the lower amount of aerial image information used in the process. In ICC, aerial images were used to measure the outlines, and in Nebel and Partner, images were used for visual interpretation purposes. It seems that good quality results can be obtained when building outlines are measured using image information. Originally, TerraScan has been developed for the use of TopEye laser data and digital aerial images (resolution a few cm) which are taken simultaneously with the laser recording. It is expected that such accurate digital camera information together with laser data provide much better accuracy concerning building outlines, but with significantly higher costs.

In Hermanni, where all participants using laser data provided a model, the ICC (based on TerraScan) model showed the best accuracy. Also, the Delft and Aalborg models (the latter developed by undergraduate students within the project) resulted in reasonably good accuracy. It should be noticed that the FOI model was fully automatic and their newest extraction algorithm was based on the use of the first and last pulse data, and last pulse data was not provided in the test, since it was not available from all test sites. C+B did exceptionally well in Espoonlahti, which was the most difficult area, but they provided only the buildings where outlines were given. One possible explanation for the variability of the C+B performance in various test sites is that since it is based on TINs, it works better than plane-based models (laser points defining a plane) with more complex and small structures. Also the Dresden model performed extremely well in Senaatti, but not in Hermanni. The number of points used in the analysis was extremely low for the Dresden model.

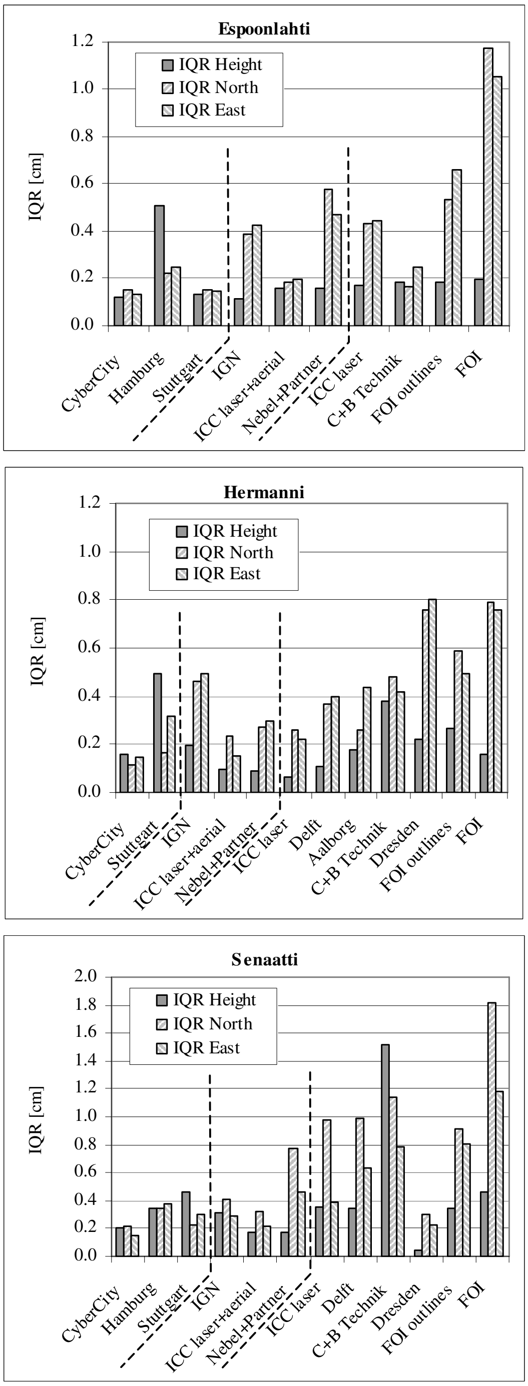

Figure 7. Location accuracy (IQR) of the models with respect to single points.

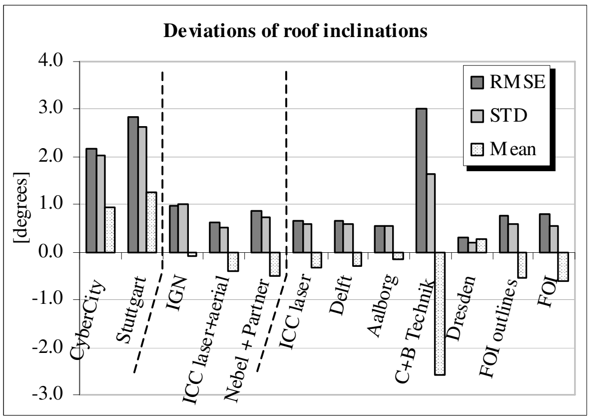

Figure 8. Roof inclination accuracy of the models.

Figure 8 gives the roof inclination accuracy of each model, defined with RMSE, in Hermanni. The best result was obtained with the Dresden model and basically all laser based methods resulted in less than 1 degree error (RMSE). The C+B approach had a larger error as well as the photogrammetric processes. Most probably the TIN based principle of C+B does not give as good results as using all the points hitting one surface and defining a plane using all of them. In photogrammetry, the roof inclination is obtained from two measurements, therefore, obviously, the same accuracy as with laser was not achieved. When the building size was smaller and/or the pulse density was lower, this difference between photogrammetry and laser scanning was reduced or even disappeared.

5. DISCUSSION AND CONCLUSION

The paper compared the performance of photogrammetric, laser scanning based and hybrid methods in building extraction, especially on the determination of building outlines, lengths and roof inclination. The paper confirms with experiments that laser scanning is more suitable for deriving building heights, extracting planar roof faces and ridges of the roofs whereas photogrammetry and aerial images are more suitable for building outline and length determination. In building outline determination, point density, shadowing of trees and complexity of the structure were the major reasons for site wise variations of the laser scanner based results. In building length determination with laser scanning, the complexity of the buildings was the major cause for site wise variation rather than the point density. Height determination accuracy followed exactly the laser scanning point density. With high-density data in Espoonlahti, all participants were able to provide average height with accuracy better 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). In general the target plane accuracy is affected by the degree of automation. The target height accuracy seems to be almost independent of the degree of automation.

CyberCity, Stuttgart and TerraScan (provided by the ICC) solutions provided the highest accuracy. There seemed to be a higher variation in the quality with other models depending on the test site or remotely sensed information.

The quality of building extraction using laser scanner data can be improved by using existing building outline information from cadastre systems, high resolution aerial images or building walls defined from planes obtained from a number of laser hits from the walls. Some systems, such as TopEye MK II, provide a large number of wall hits when flying along the street in city due to the conical scanning mechanism (scanning angle constant).

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