

A QUALITY ASSESSMENT OF REPEATED AIRBORNE LASER SCANNER OBSERVATIONS

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ABSTRACT:

This paper describes the height and planimetric errors of repeated ALS (airborne laser scanning) strips with a deeper focus on building extraction. Measurements with Toposys Falcon airborne laser scanner were arranged in May 2003 in Espoo, Southern Finland. A 5 km² test area, consisting of urban settlements and forests, were collected from the altitude of 400 m resulting in measurement density of about 10 points per square metre. One 4 km long and about 100 m wide strip was collected five times allowing the analysis of the repeatability of the laser scanning. One strip was used as a reference and inter-strip comparisons were made. Point wise comparison methods were also used to characterize the differences. Additionally, target models were compared against each other. Real Time Kinematic (RTK) GPS and also tachymeter measurements were used as ground reference. Extraction of building vectors from laser scanner data was performed using interactive methods implemented in the TerraScan software. The accuracy of the vectorization is also reported. Mean height errors for elevation points were –2 to 1 cm and standard deviations were mainly ± 3 –4 cm. In planimetry, mean errors of the centre points of the buildings were less than 30 cm for the first and also for the last pulse data when compared with the buildings on the map. The standard deviations varied between ± 11 –28 cm (first pulse) and ± 14 –18 cm (last pulse) for extracted buildings using repeated observations. Mean errors were between 3–8 cm and standard deviations ± 3 –6 cm using last pulse data of repeated observations and extracted ridge information. Extracted buildings were systematically larger from first pulse data than from last pulse data.

1. INTRODUCTION

Airborne laser scanning (ALS) produces 3D information about the object, giving both the terrain elevations and 3D target models. The original output of the ALS is a point cloud containing x, y and z coordinates and intensity values of the points. The main applications of airborne laser scanning are digital elevation models, but it can be used successfully for e.g. 3D city modelling, power line corridor mapping, forest mapping, urban planning, water resource management and railway surveying. More and more applications will appear as the ALS equipment and analysis methods improve all the time. Quality of airborne laser scanning has been studied for many years (e.g. Crombaghs et al., 2002; Maas, 2002). Rönnholm (2004) has studied the repeatability of laser scanning strips by analyzing the shifts of local laser point clouds with the interactive orientation method (Rönnholm et al., 2003). The measurement accuracy of the laser points for different sensors is reported in (Baltsavias, 1999). Building modelling accuracy in position and in elevation has been reported by Steinle et al., (2000). Maas et al. (1999) used raw laser altimetry data and two methods, the intersection of planar faces and the analysis of invariant moments methods, to model buildings. The invariant moments method yielded a precision of 0.1–0.2 m for the building dimensions.

2. MATERIAL AND METHODS

2.1 Airborne laser scanner data

Toposys Falcon airborne laser scanner measurements were carried out in May 14th, 2003 in Espoonlahti area, Southern Finland. A 5 km² test area, consisting of urban settlements and forests, were collected from the altitude of 400 m resulting in nominal measurement density of about 10 points per square metre. One 4 km long and about 100 m wide strip was collected five times. First and last pulse data with intensity values were recorded. Technical details about the Toposys Falcon laser scanner system can be found in (www.toposys.com) and are summarized in Table 1. A constant elevation adjustment for the whole strip was done by Toposys. In their method the value of the correction was determined at the overlaps of the flight strips in the profiles that were running across the flight strips. The Z correction was –0.03 m for strips ID number 2, 3 and 4 and –0.01 m for strips 5 and 6. Strips 3 and 5 were flown to the southeast direction and strips 2, 4 and 6 to the northwest direction.

Sensor type	Pulsed fibre scanner
Range	1600 m
Distance resolution	0.02 m
Scan width	14° ($\pm 7^\circ$)
Scan rate	653 Hz
Laser pulse rate	83 000 Hz
Pulse length	5 ns
Laser wavelength	1560 nm
Data recording	First and last echo, intensity

Table 1. Technical parameters of the Toposys Falcon airborne laser scanner.

2.2 Ground truth data

Ground truth data were collected in Espoonlahti area. Reference points were measured with a robotic tachymeter Trimble 5602 DR200+. Altogether 4500 asphalt and gravel reference points were used in comparison. They were situated in the area of about 210 by 140 m². A building map with vectors was obtained from the City of Espoo. 58 corner points of the roofs were measured with Leica SR530 Real-Time-Kinematic RTK GPS. The distance between the rover and the reference station was about 1300 m during the measurements.

2.3 Comparison of laser points with reference points

Elevations of airborne laser scanner derived points were compared with the robotic tachymeter reference points. A circle with a radius of 2 m using a reference point as a centre point of the circle was created for every reference point. Statistics of the ALS points were calculated inside the circles if there were more than 5 laser points included. Mean value, median, minimum, maximum and standard deviation, nearest laser point to the reference point and an interpolated height value from the laser points were calculated. A 10 cm by 10 cm grid and a cubic method was used in the height interpolation calculations. A maximum value of 0.2 m for standard deviation inside the circle was used as a homogeneity measure of the points. Laser observations from the bushes, trees and buildings are kept out of the calculations this way. The same method has been used in (Ahokas et al., 2003).

2.4 Building extraction

Building vectorization was done by using the TerraScan software developed by Terrasolid Ltd. (www.terrasolid.fi). Laser points were first classified to ground class. Then building class was classified by height from ground, e.g. minimum height for a house must be 2 m above ground. The places of possible buildings were then known and the building construction could be started. By pointing a cursor to the possible building location and clicking the mouse, the program started to find planar surfaces inside the search area resulting in a list of planes with the information about boundary colour, slope angle, number of points matching plane, average mismatch from point to raw and adjusted plane. User could also search for additional planes if there were small, undetected parts in the house. When the correct number of planes was reached the boundary tools could be applied. The boundary type of a plane could be set to a rectangle with four 90 degree corners, to rectangular with 4 to N 90 degree corners or to a free shape polygon. Boundary shapes could be modified so that a vertex or a segment can be moved. A vertex could be also removed from a boundary. Pieces could be cut off from a corner or a segment. Boundary lines were auto aligned with intersection lines and with each other. When we were satisfied with the building the model was applied and the work with the next building started.

3. RESULTS

3.1 Analysis of height errors

The calculated laser point heights (c.f. section 2.3) were compared to the heights obtained with the robotic tachymeter. Firstly, mean height error between the reference point and the nearest laser point was calculated. Secondly, also the mean height error between the laser point and the interpolated height

value was obtained. Results are in Tables 2 and 3. Each flight strip was analyzed separately.

Flight strip	2First	3First	4First	5First	6First
Nearest point z	-1±4	0±4	0±4	1±4	1±4
Interpolated z	-1±3	0±3	0±3	1±3	1±3

Table 2. Mean height errors (Laser-Tachymeter) and standard deviations of differences for asphalt and gravel ground. First pulse mode observations. Results are in cm. 2First is the strip number 2, first pulse data.

Flight strip	2Last	3Last	4Last	5Last	6Last
Nearest point z	-2±4	0±9	0±4	0±4	0±4
Interpolated z	-2±3	0±3	0±3	0±3	1±3

Table 3. Mean height errors (Laser-Tachymeter) and standard deviations of differences for asphalt and gravel ground. Last pulse mode observations. Results are in cm. 2Last is the strip number 2, last pulse data.

It can be concluded that in the reference point area the systematic error was negligible. Additionally, 3-4 cm standard deviation is quite small for such plane targets. The decimetre accuracy obtained with the strip 3 with nearest point method at last pulse mode is also acceptable.

3.2 Analysis of planimetric errors using centres of buildings and ridges

An area covering 39 buildings was extracted from the five overlapping flight strips using methods depicted in section 2.4. Due to the turnings of the airplane, at least 30 buildings could be identified from all flight strips. Houses were grouped by their roof types into five categories: hipped roof, double slope pitch roof, flat or pitch roof, ridge roof and connected ridge roof. The extraction of the hipped and connected ridge roof type buildings required more manual work than e.g. ridge roof buildings.

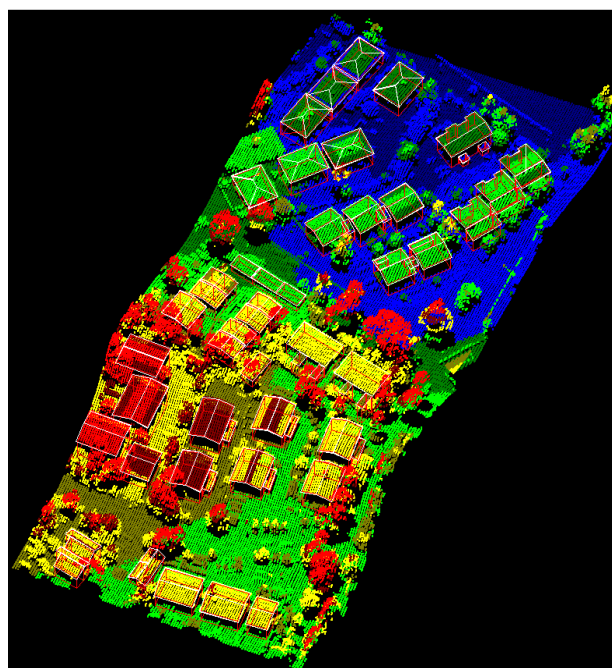


Figure 1. A rotated oblique view of the flight strip number 3 (first pulse) laser points and the extracted buildings.

The use of centres of buildings

The distances between the laser derived building centre point and the corresponding centre point from the building map were calculated, as well as the distances between the centre points of buildings using the first pulse data and the corresponding buildings using last pulse data. Lines between opposite corner points of the extracted buildings determined the centre point of the building. Results are shown in Tables 4, 5 and 6.

Flight strip	2F-map	3F-map	4F-map	5F-map	6F-map
Min dist.	7	4	9	1	4
Max dist.	161	67	61	53	69
Mean \pm Std	28 \pm 28	23 \pm 16	27 \pm 11	18 \pm 12	24 \pm 15

Table 4. Distances (cm) between the centre points of the first pulse mode derived buildings and map buildings.

Flight strip	2L-map	3L-map	4L-map	5L-map	6L-map
Min dist.	7	4	6	1	6
Max dist.	73	52	68	63	82
Mean \pm Std	25 \pm 15	23 \pm 14	27 \pm 14	19 \pm 15	28 \pm 18

Table 5. Distances (cm) between the centre points of the last pulse mode derived buildings and map buildings.

Flight strip	2F-2L	3F-3L	4F-4L	5F-5L	6F-6L
Min dist.	1	2	1	1	1
Max dist.	41	51	68	35	77
Mean \pm Std	13 \pm 10	17 \pm 13	12 \pm 12	14 \pm 9	18 \pm 16

Table 6. Distances (cm) between the centre points of the first and last pulse mode derived buildings.

Mean distances of the centre points of the extracted buildings were less than 30 cm for the first and also for the last pulse data when compared with the buildings on the map. The standard deviations varied between ± 11 -28 cm for the first pulse and ± 14 -18 cm for the last pulse. Maximum distances were mainly less than the Toposys Falcon scan line distance, about 80 cm, in the across track direction. It was difficult to find the exact boundaries for some buildings because they were partly covered by trees. This is one reason for the large errors in distances when using the first pulse data. Distances between the centre points of the first and last pulse mode derived buildings coincide better with each other than with the map buildings. Mean errors (12-18 cm) and standard deviations (± 9 -16 cm) from one flight strip include errors resulting from the building extraction modelling and from the different observation modes.

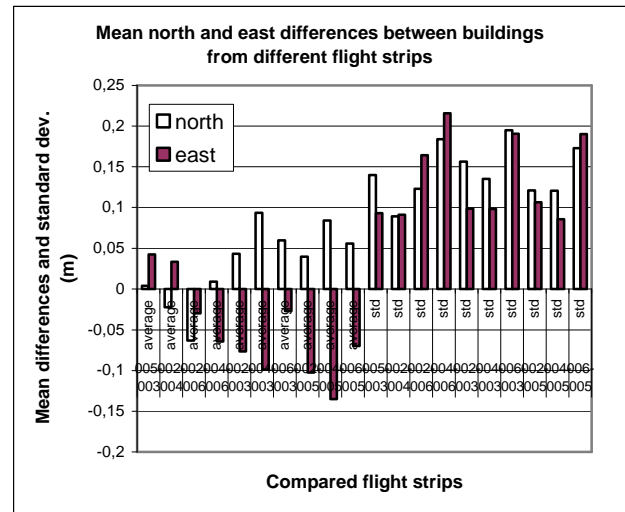


Figure 2. Planimetric errors of last pulse flight strips. 3 and 5 were flown to the southeast and 2, 4 and 6 to the northwest. 002-003, 004-003, 006-003, 002-005, 004-005, 006-005 are opposite directions.

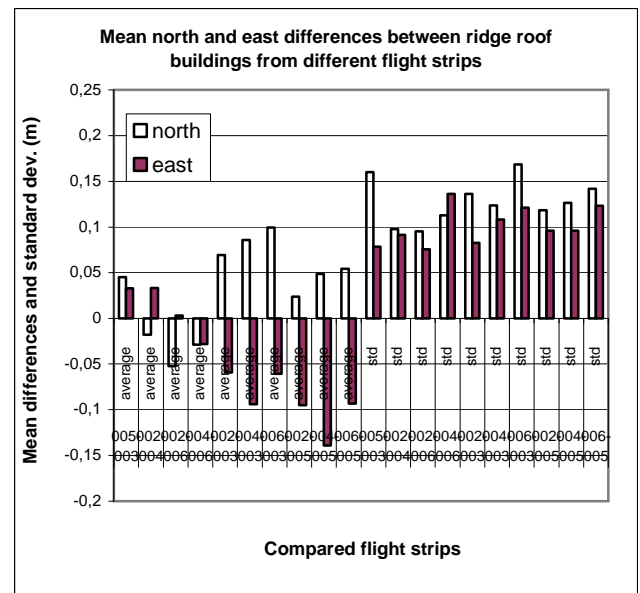


Figure 3. Planimetric errors of last pulse flight strips. 3 and 5 were flown to the southeast and 2, 4 and 6 to the northwest. 002-003, 004-003, 006-003, 002-005, 004-005, 006-005 are opposite directions. Only ridge roof buildings included.

As mentioned in section 2.1, strips number 3 and 5 were flown to the southeast direction and 2, 4, 6 were flown to the northwest direction. We had two cases to compare. Firstly, flight strips to the same directions were compared and secondly, also the opposite direction flight strip comparisons were carried out, Figures 2 and 3. In Figure 3 only the ridge roof buildings were included because they were the biggest group and easiest to extract.

In Figures 2 and 3 the first four columns (average values) on the left are the same flight direction pairs. Columns five to ten

(average values) are the opposite direction pairs. The results are significantly different between them. It seems that the centre points of the buildings have moved about 5 cm to the flight direction. There is an across track shift (<5 cm) between the flight strips with the same flight direction. The standard deviations of the differences for opposite direction flight strips are larger than for the flight strips to the same direction. To conclude, the results indicate that the flight direction was a significant reason for planimetric errors.

In Figure 4 comparisons were made between the last pulse data and the Espoo city map buildings. The coordinate transformation from the Espoo system to the Finnish national system ksj also brings some errors to the results. There is a systematic shift of the map buildings to the east (northeast) compared to the laser derived buildings.

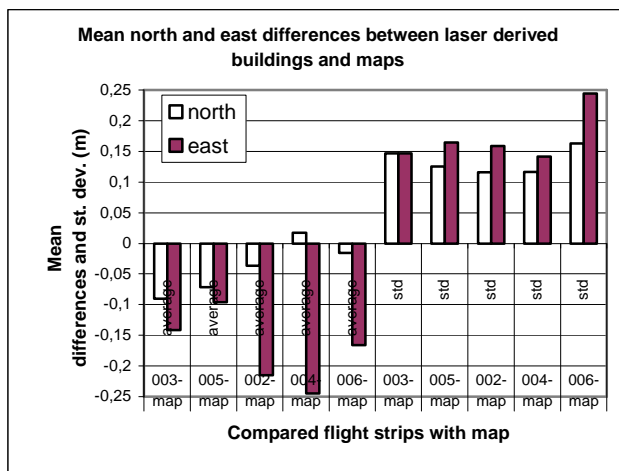


Figure 4. Comparison of different last pulse flight strips with map buildings. 3 and 5 were flown to the southeast and 2, 4 and 6 to the northwest.

The use of ridges of buildings

A ridge of a building roof can be obtained in a more accurate way than the edges and corner points of the building since the ridge is defined by two intersecting planes that are determined using even hundreds of laser points. Thus, previous conclusions were checked by calculating the shift of the ridges between repeated acquisitions. Table 7 summarizes the comparison of these two approaches.

Compared flight strips		Distance between	
		Centre points	Ridges
Same direction	5-3	14±12	5±3
	2-4	11±8	4±4
	2-6	9±9	3±4
	4-6	14±11	5±5
Opposite direction	2-3	13±13	6±5
	4-3	17±12	8±6
	6-3	18±15	6±6
	2-5	16±8	7±4
	4-5	20±9	7±4
	6-5	19±9	7±4

Table 7. Mean differences and standard deviations (cm) calculated from centre points and ridges of ridge roof buildings. Last pulse data.

The compared flight strips and the modelling method of the buildings are the same. Again flight strips to the same direction gave smaller biases than the flight strips to the opposite directions. However, obtained errors are significantly smaller using ridges than centre points of buildings.

3.3 Analysis of size of buildings

The areas of the roofs were measured along the slopes (i.e. to the normal of the roof). Areas were calculated for every building as a mean value of the five flight strips. The differences between the first and the last pulse mode derived roof areas in percentage were calculated for each building and the mean values were obtained for each roof type, c.f. Table 8.

Roof type and #		First pulse flight strips	Last pulse flight strips	Mean difference
Hipped roof, N=6	Mean area minimum	163.0 m ²	145.9 m ²	11.6 %
	Mean area maximum	166.8 m ²	151.3 m ²	
Double slope pitch roof, N=3	Mean area minimum	165.7 m ²	145.6 m ²	14.0 %
	Mean area maximum	167.8 m ²	146.8 m ²	
Flat or pitch roof, N=5	Mean area minimum	17.9 m ²	16.3 m ²	4.4 %
	Mean area maximum	171.6 m ²	159.7 m ²	
Ridge roof, N=20	Mean area minimum	94.3 m ²	58.8 m ²	13.2 %
	Mean area maximum	234.8 m ²	211.5 m ²	
Connected ridge roof, N=5	Mean area minimum	88.3 m ²	85.8 m ²	11.4 %
	Mean area maximum	189.8 m ²	170.5 m ²	

Table 8. Mean differences between the first and the last pulse mode derived roof areas.

The buildings were one- or two-storied and relatively small ones. Differences between the first and the last pulse measured areas were 11-14 % except for the flat/pitch roofs (4.4 %) when the trees obstructed the views of these roofs. This flat or pitch roof building group included also car shelters that were lower than the human settlements. The first pulse mode observations tend to exaggerate the area and the last pulse data systematically underestimate the results.

Roof lengths were calculated from the RTK measured roof corner points and these lengths were compared with the laser derived roof lengths. The laser derived roof lengths were actually the side lengths of the extracted roof planes. Because the Toposys laser scanner has a special scan pattern the lengths were divided to three categories: lengths across the flight strip, along the flight strip and oblique to the flight strip. The distance between the scan lines across the flight strip direction is about 80 cm (footprints of neighbouring fibres) when the flying height is 400 m. In the along track direction the pulses overlap on the ground. Results are shown in Tables 9 and 10.

Direction of edge	2F-RTK	3F-RTK	4F-RTK	5F-RTK	6F-RTK
Across	34±13	21±16	18±49	-30±38	21±7
Along	7±7	15±3	14±11	24±12	13±9
Oblique	19±46	31±31	34±25	27±28	21±49
Total	20±37	27±26	26±31	13±36	19±38

Table 9. Mean differences (cm) and standard deviations of the roof lengths from first pulse mode observations and RTK measurements.

The mean difference of the roof lengths across the flight strip number 5 (first pulse) is negative. In this case, the laser observations from the edge of some roofs were not accepted to the roof plane because their undulations were too big. Hence the roofs became shorter than in reality. The along flight strip results for the first pulse mode observations (7-24 cm) are expected to be smaller than the across flight strip results (18-34 cm) because of the scan pattern. The standard deviations were quite small, between ± 3 -12 cm. In total the roof lengths from the first pulse mode are about 21 cm longer than the reference lengths from RTK measurements.

Direction of edge	2L-RTK	3L-RTK	4L-RTK	5L-RTK	6L-RTK
Across	-52±30	-40±11	-26±8	-81±13	-29±5
Along	-35±32	-48±2	-37±21	-32±22	-47±3
Oblique	-18±31	-9±39	-7±23	-12±16	-13±28
Total	-29±33	-21±36	-19±23	-32±33	-23±25

Table 10. Mean differences (cm) and standard deviations of the roof lengths from last pulse mode observations and RTK measurements.

The last pulse mode results in Table 10 for the along track direction do agree with the relation depicted in Table 9 between across and along track directions. Again the across track value (-81 cm) of the flight strip number 5 indicates the shortest roof lengths. In total the roof lengths from the last pulse mode are about 25 cm smaller than the reference lengths from RTK measurements.

4. DISCUSSION

The obtained elevation accuracy for repeated strips was good. Also planimetric errors were mainly detected by comparing strips flown with opposite directions.

The mean height errors for elevation points were -2 to +1 cm and standard deviations were mainly ± 3 -4 cm and for one strip it was ± 9 cm. These values are comparable to other previous results for planar targets (e.g. Ahokas et al., 2003).

Centre points and ridges of the extracted buildings were used to test how small planimetric changes in the laser data affect the obtained building model. Therefore, we also indirectly analyzed the accuracy of the building extraction model. In paper by Rönnholm (2004), a similar description of the systematic internal quality of repeated measurements using point cloud data is given.

The mean distances between the centre points of the buildings derived from the first and last pulse observations differed less than 20 cm from each other while the standard deviation was ± 9 -16 cm (Table 6). In one flight strip these errors include the building extraction modelling errors and the errors resulting

from the differences between the first and the last pulse data. Normally the shape of the building was the same, only area was changed. When we compared the mean distances between the centre points of the laser derived buildings and buildings on the map, less than 30 cm differences occur. Standard deviations were ± 11 -28 cm and ± 14 -18 cm (Tables 4 and 5). These mean errors include the building extraction modelling errors, the systematic shift between the transformed map and laser coordinates and also the along track shift of the laser observations to the flight direction. This gives information how well the buildings can be extracted in real life from laser scanner data. Vögtle et al. (2000) reported that the interior accuracy of the modeled buildings is about ± 20 -30 cm in position and ± 5 -10 cm in elevation. When they compared the wireframe model with the manually derived CAD model the coordinate differences were about ± 20 -90 cm in xy and about ± 20 cm in z. Steinle et al. (2000) reported the differences between the first and last pulse derived wireframe models. In this case the first and last pulse flights were from different dates and the grid size was $1 \times 1 \text{ m}^2$. Mean differences were about 0.8-1.5 m in xy and about 0.2-0.6 m in elevation.

First and last pulse data give different results for building sizes. The total mean differences of roof lengths from first and last pulse varied from about -30 to +30 cm and the standard deviation was less than ± 40 cm (Tables 9 and 10). Buildings were of different size and orientation. Some errors are by inheritance from the observation geometry of the Toposys ALS. An internal precision of 10-20 cm for dimensions of 10 buildings was reached in a study of Maas et al. (1999). The FLI-MAP system produced a point density of 5 points/ m^2 .

The results showed that the same ridge can be extracted by repeated measurements with less than 3-5 cm systematic error and the standard deviation of the shifts between acquisition was less than 5 cm when using strips flown in the same direction. In general this implies that the ridges extraction is very accurate and the repeatability of the laser scanning with Toposys Falcon is good.

5. CONCLUSIONS

The repeated observations of five Toposys Falcon flight strips from Espoonlahti area were compared with each other and with reference data.

Using reference measurements, the systematic height errors for elevation points were -2 to +1 cm and standard deviations were mainly ± 3 -4 cm. It can be concluded that the changes in height errors of these five strips is negligible.

In planimetry, mean distances of the centre points of the buildings were less than 30 cm for the first and also for the last pulse data when compared with the buildings on the map. The standard deviations varied between ± 11 -28 cm (first pulse) and ± 14 -18 cm (last pulse) in different flight strips. The planimetric accuracy of the object (building) on the ground depends on the direction of the flight. There is an along track shift of about 5 cm to the flight direction. The accuracy obtained using the centre points of the buildings depends on the extraction accuracies and the distribution of the laser points on the ground. Results obtained using the ridges confirmed that there is a difference in planimetric accuracy between the flight strips to the opposite direction and to the same direction. Biases were 3-5 cm and standard deviations ± 3 -5 cm for the flight strips to the

same direction. Correspondingly, biases were 6-8 cm and standard deviations ± 4 -6 cm for the flight strips to the opposite directions. To summarize, the planimetric accuracy is worse than vertical but acceptable for various purposes.

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The first pulse mode observations tend to exaggerate the area and the lengths of the roofs. The first pulse data give about 11-14 % larger building roofs than the last pulse data. Lengths of the roofs were about 21 cm longer from the first pulse data than in reality. Correspondingly, the last pulse mode gives underestimated results. Lengths were about 25 cm smaller than the obtained reference measurements. These systematic effects have to be realized e.g. in cartographic applications.

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