ANALYSIS OF PLANIMETRIC ACCURACY OF AIRBORNE LASER SCANNING SURVEYS

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Commission III, WG III/3

KEY WORDS: Laser scanning, 3-D feature extraction, aerial survey, accuracy analysis, buildings

ABSTRACT:

With the increasing pulse rates of airborne laser scanners point clouds become an interesting data source for mapping beyond the production of digital terrain models. Whereas height accuracy of point clouds is of prime importance for terrain models, mapping of buildings and other objects also requires an analysis of planimetric accuracy of point clouds. This paper presents a methodology to estimate relative strip offsets and standard deviations of X- and Y-coordinates using automatically extracted ridge lines of buildings in overlaps between strips. An analysis of three blocks with 200-250 million points each shows that constant strip offsets explain the majority of planimetric shifts between ridge lines in strip overlaps. It is demonstrated that strip offsets below 3-4 cm and platform positioning noise of only 2 cm can be obtained with GPS configurations consisting of two onboard receivers and multiple reference stations in the terrain and a low flying height.

1. INTRODUCTION

In the last decade airborne laser scanning has rapidly become the preferred technology for the acquisition of digital terrain models. Traditional fields of applications, like water and forest management, required high height accuracies, but were less demanding with respect to planimetric accuracy (Crombaghs et al., 2000, 2002; Ahokas et al., 2003), in particular in areas with moderate terrain slope.

In recent years, pulse frequencies of laser scanners increased to nowadays up to 250 kHz. With such scanners point clouds can be acquired with 10-20 points / m^2 from low speed aircrafts or helicopters. These point densities enable applications like mapping building contours (Clode et al., 2004; Wang et al., 2006; Sohn and Dowman, 2007; Sampath and Shan, 2007), change detection (Matikainen et al., 2003; Vosselman et al., 2004, Vu et al., 2004) and 3D building modelling (Brenner, 2005; Rottensteiner, 2003). For this kind of mapping applications, the analysis of planimetric accuracy is highly relevant.

The accuracy with which objects can be outlined in point clouds depends on the point distribution around the object's outline as well as on the location accuracy of the laser points. In the worst case (scan lines parallel to object outline), the uncertainty due to the point distribution is equal to the distance between the scan lines. The location accuracy of the laser points depends on the systematic and stochastic errors in the GPS, IMU, mirror angles, and range measurements. Vosselman and Maas (2001) showed that the effects onto planimetry are often much larger than onto the height. Several approaches for strip adjustment have been presented to estimate and correct for specific instrumental errors (Burman, 2000; Kager, 2004). The effects of these errors on the laser point coordinates are often difficult to separate. For mapping purposes, however, this does not need to be a major concern, as long as it is known that the combined effect of the measurement errors onto the point coordinates is below some error level.

To analyse both planimetric and height accuracies of laser point clouds, Csanyi and Toth (2007) designed special ground targets. Target coordinates measured in the point clouds were compared those surveyed with GPS and resulted in estimated planimetric accuracy of 5-10 cm and height accuracy of 2-3 cm. While especially designed targets allow an accurate analysis, for most laser scanning projects it will not be feasible to set up many targets in the field.

In this paper a largely automated analysis of planimetric accuracy of several laser scanning surveys is presented which makes use of building roofs. Ridge lines of gable roofs can accurately be extracted from point clouds (Vosselman, 2002). As ridge lines are estimated as lines of intersection of two extracted roof planes, their location is not affected by the distribution of points around the ridge line. Hence, their accuracy can be completely attributed to measurement errors of the sensors. An estimate of the measurement accuracy is obtained by comparing ridge line locations extracted from overlapping strips. Although this comparison is relative between the strips, and therefore does not include a check on the absolute georeferencing of the block, it does show distortions of the point clouds and allows estimating the stochastic planimetric accuracy. Because many points are usually located on both roof faces of a gable roof, the noise in the range measurements will be largely eliminated by the plane fitting. Offsets between ridge lines in overlapping strips should therefore be explained by systematic and random errors in the GPS and IMU measurements.

After describing the characteristics of the processed laser scanning blocks in the next section, the method to extract the ridge lines and estimate strip offsets is presented in section 3. The results of the processed blocks are analysed in section 4.

2. DATA SOURCES

Three datasets were analysed for the presented study. The first dataset consists of 16 strips acquired for the Dutch national elevation model AHN over the province of Brabant. The overlap between the strips is quite small, because the data provider removed the ends of the scan lines (Table 1). This, of course, also reduced the amount of roofs that could be extracted from the overlap. The second dataset is a small part of the recently conducted pilot study to acquire a high point density elevation model over the province of Zeeland. The third dataset was acquired last year over the city of Enschede with a point density of 20 pts/m^2 (Fig. 1). Data of this survey was delivered in three files per strip, corresponding to the forward, nadir and backward looking scan lines. To speed up the processing only data from the nadir looking scan lines was used, reducing the point density to 10 pts/m^2.

Block	# strips	# pts x 10^6	# pts / m^2	Strip width (m)	Overlap (m)	Flight height (m)
Brabant	16	218	0.5	550	55	1000
Zeeland	9	241	10	460	100	375
Enschede	15	254	10	330	100	275

Table 1: Characteristics of the datasets.

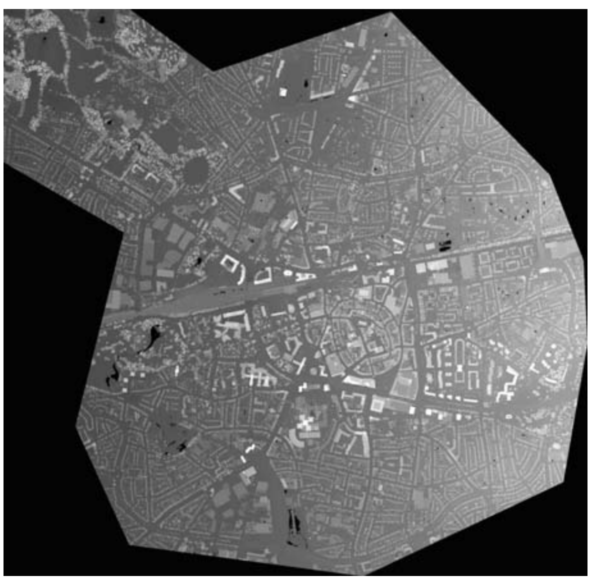


Figure 1: Height image of the Enschede dataset.

Both the Zeeland and Enschede dataset were acquired with the FLI-MAP 400 system of Fugro-Inpark mounted in a helicopter (Fugro, 2007). Two GPS receivers on board of the helicopter were combined with multiple reference stations on the ground to determine the platform position. In case of the Zeeland dataset around five reference stations were used simultaneously. In case of the Enschede dataset three reference stations, one of them virtual, were used.

3. MEASUREMENTS OF STRIP OFFSETS

3.1 Data preparation

With some 10-20 million points per strip datasets can not be processed in computer memory in one piece but need to be split up. After determining the points in the overlap area between two strips, the overlap is split into pieces of some one million points.

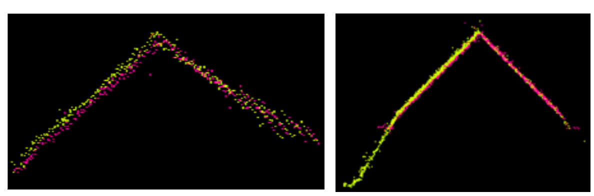
3.2 Extraction of ridge line pairs

For each piece of an overlap, the point clouds of both strips are first segmented into planes. This segmentation is done with a surface growing algorithm using a 3D Hough transform for detection of seed surfaces (Vosselman et al., 2004). As the Hough transform may be time consuming on large datasets, it was only applied to sets of 20 points to detect the presence of a plane. When a plane was found, the distance of nearby points (defined by a kd-tree) to the plane were tested and a point was added to the now growing surface when the distance was below some threshold. The parameters of the plane were re-estimated after adding points to the surface. However, to speed up the algorithm, this was only done after the number of points in the surface increased with 50%.

Planar segments of a minimum number of points and a slope in between 30 and 70 degrees are selected for further processing. For all pairs of nearby segments, an intersection line is computed. If both segments have points near a common part of this intersection line, a ridge line is found. Once ridge lines have been extracted from both strips, they have to be matched to determine the ridge line pairs. Two ridge lines are considered to correspond to the same building ridge if the ridge lines have a similar orientation and the centre point of one ridge line segment is within some distance of the ridge line in the other strip.

The extraction of ridge line pairs is performed in a batch process for complete blocks. For the Enschede block, which had most points in the overlap, processing took about 20 hours on a 2 GHz PC with 2GByte RAM.

Occasionally, incorrect ridges are extracted due to errors in the segmentation step. Two examples are shown in Fig. 2. The right face of the roof in Fig. 2(a) is non planar as can be seen from the large dispersion on the far right side. Still these points were classified as belonging to the same plane. In Fig. 2(b), the segmentation algorithm failed to distinguish between to nearly parallel planes.



(a) (b)

Figure 2: Segmentation errors due to (a) a non-planar surface or (b) under-segmentation of two planes with slightly different slopes. Points from two strips in yellow (bright) and pink (dark).

In such cases the derived ridge lines are often incorrect. In particular when under-segmentation occurs in one strip, but not in the overlapping strip, the ridge line positions will differ and result in an incorrect offset estimation. A manual inspection step was therefore included to avoid that erroneous ridge lines were used in the computation of the strip offsets. Point clouds and ridge lines were inspected when the offsets in height or planimetry between the ridges were larger than twice the average offset sizes. For the Enschede dataset this resulted in 72 ridge line pairs to be removed out of the total number of 2115 detected pairs.

For the low point density dataset of Brabant (0.5 pts/m^2), all buildings had to be checked manually. This was required to eliminate measurements on buildings like the one in Fig. 3. The points of two strips are shown in green (bright) and purple (dark). Because of the large distance between the scan lines and the usage of an oscillating mirror, the southern roof part is only covered by two nearby parallel scan lines in the strip shown in purple. Such a configuration of points would lead to an unreliable estimation of the slope of the roof plane and therefore also result in an unreliable estimation of the ridge line. Such cases could be detected automatically by inspection of the theoretical variances of the estimated plane parameters or a check on the sizes of the eigenvalues of the moment tensor of the point cloud. In the latter case, two small eigenvalues would indicate that all points are nearly collinear. For the purpose of estimating the ridge lines with cm accuracy, the point set on a roof face is good enough if it contains at least ten points and has a minimum bounding rectangle with a width of at least 1 m.

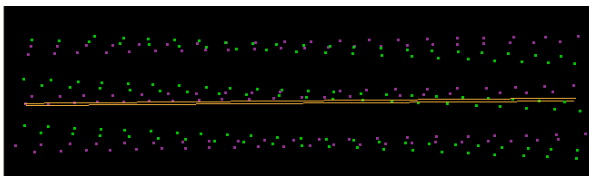


Figure 3: Roof planes with only two nearly collinear scan lines.

3.3 Offset computations

Offsets have been computed between complete strips as well as for small strip parts.

3.3.1 Strip offsets: A ridge line pair in an overlap will only give information on the offset perpendicular to the ridge line. In order to determine two dimensional offsets between strips, the information of all ridge lines in an overlap has been combined. Let (x_1, y_1) be the position of the centre of a ridge line in strip 1 and let

$$x\cos\alpha_2 + y\sin\alpha_2 - d_2 = 0 \tag{1}$$

define the corresponding ridge line in the overlapping strip 2. The distance between the two ridge lines is then calculated as

$$e = x_1\cos\alpha_2 + y_1\sin\alpha_2 - d_2 \tag{2}$$

and the distance after applying an offset (Δx, Δy) as

$$e = (x_1 + \Delta x)\cos\alpha_2 + (y_1 + \Delta y)\sin\alpha_2 - d_2 \tag{3}$$

The offsets (Δx, Δy) between the strips have been computed such that the square sum of all distances between the corresponding ridge lines in an overlap was minimised.

3.3.2 Local offset vectors: To obtain insight into drifts in the determination of the sensor position, it is useful to compute offsets at multiple locations in a strip overlap. Therefore, offsets were computed for every set of five nearby ridge lines. In case all ridge lines in a set had a similar orientation, estimation of a two-dimensional offset vector is, of course, not possible. In this case additional ridge lines were added until the ridge line orientations spanned a range of at least 45 degrees.

4. ACCURACY ANALYSIS

For the three different blocks, offsets between the strips were computed with the above described method. Furthermore, the root mean square value of the distances between the corresponding ridge lines was calculated. After applying the offsets to the ridge lines of one strip, the remaining differences between the corresponding ridge lines were used to calculate the standard deviation of the planimetric misclosures. Local offset vectors for sets of a few buildings were only derived for the Enschede dataset. In the Brabant dataset as well as in the Zeeland dataset insufficient ridge lines were available to study the offset drift in the overlaps. In the Brabant dataset this was due to the low point spacing as well as the narrow overlap. The Zeeland dataset was recorded in a very rural area with only one small village and hence contained only few buildings.

4.1 Brabant dataset

Fig. 4 shows the height image of the 16 strips of the Brabant dataset together with the location of the extracted roof ridges. The estimated offsets and accuracies are given in Table 2. Strip 56 was split in a western and eastern part, denoted by 56W and 56E respectively. The offsets in flight direction (X-direction) clearly show alternating high and low values. Most likely these offsets are caused by a boresight misalignment in the pitch rotation. As the terrain in this dataset has little height variation, one would expect that an offset would be sufficient to largely remove the discrepancies between the strips.

Strip 1	Strip 2	# Roofs	Δx (cm)	Δy (cm)	RMS (cm)	StDev (cm)
53	54	23	-46.1	28.6	39.3	8.0
54	55	20	-23.3	25.9	27.5	7.7
55	56W	18	-29.3	31.1	36.6	4.1
55	56E	5	-44.8	25.2	26.1	2.4
56W	57	11	6.3	28.3	22.7	9.1
56E	57	4	6.0	34.4	29.8	2.1
57	58	25	-53.1	38.7	48.5	5.5
58	59	18	6.3	32.1	25.0	5.5
59	60	22	-61.2	43.4	57.3	7.8
60	61	17	-2.9	27.5	20.7	7.4
61	62	20	-48.9	40.7	49.2	5.9
62	63	19	7.9	29.0	24.1	13.8
63	64	19	-59.4	36.1	55.6	8.0
64	65	21	7.0	30.0	25.1	12.9
65	66	20	-67.8	29.7	51.3	17.6
66	67	7	9.9	31.9	23.0	5.7
67	68	5	-63.2	33.1	50.4	3.5

Table 2: Offsets and accuracies of the Brabant dataset

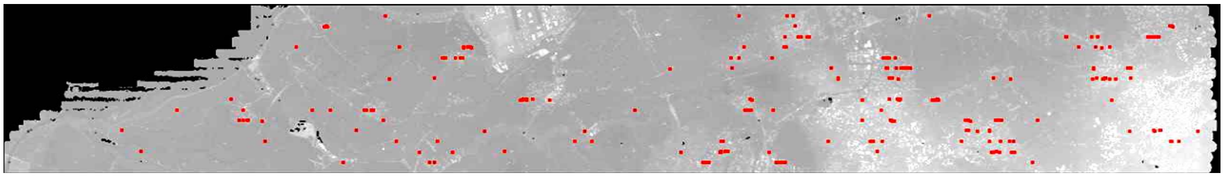


Figure 4: Distribution of 257 roof measurements in the Brabant dataset

After applying the offsets, the standard deviations computed from the remaining ridge line residuals indeed are significantly lower than the RMS values. However, the planimetric accuracy is not homogeneous, but varies between 5 and 18 cm[1]. This indicates the presence of small non-constant deformations of the strip point clouds.

4.2 Zeeland dataset

Considering the relatively low flying height and usage of multiple reference stations, offsets in the investigated strips of the Zeeland block were quite high (Table 3). In this case the offsets were caused by a malfunctioning IMU which was already noted by the service provider. In most overlaps the effect of this error onto the planimetric strip offsets proved to be largely constant. Hence, the standard deviations after applying the offsets were again significantly lower than the RMS values. This was not the case for the last overlap (bottom row of Table 3). Here, the application of the relatively small offset did not lead to a significantly lower square sum of residuals.

# Roofs	Δx (cm)	Δy (cm)	RMS (cm)	StDev (cm)
9	-28.4	7.6	18.6	1.5
65	-10.2	-10.1	9.6	3.7
11	-13.0	-12.0	15.9	6.0
29	-14.1	-33.0	26.3	9.9
53	-21.7	-39.7	33.1	6.0
15	-4.7	-8.7	17.4	16.0

Table 3: Offsets and accuracies of the Zeeland dataset

4.3 Enschede dataset

Fig. 5 shows the locations of the ridge lines extracted from the Enschede dataset. The areas in the overlap are shown in yellow (light grey). Green (dark grey) areas are only covered in one strip. In the south west part of the dataset a small area was covered by three strips, causing a wide yellow area with two or threefold overlaps. A total number of 2043 ridge lines were extracted (Fig. 5). Although the distribution of ridge lines over the area is inhomogeneous, all strip overlaps contain at least 50 ridge lines. This allows an accurate estimation of the offsets as well as an analysis of drifts within an overlap.

The offsets, RMS values and standard deviations in Table 4 show that this block has a very high accuracy. Without applying any corrections, the RMS values of the offsets between ridge lines are below 8 cm for all strip overlaps. The offsets between the strips are typically in the order of only 2-3 cm with the exception of the offsets between strip pairs 16-18, 10-7 and 9-8.

[1] The standard deviations that are even lower are not reliable as they were computed from only a few buildings.

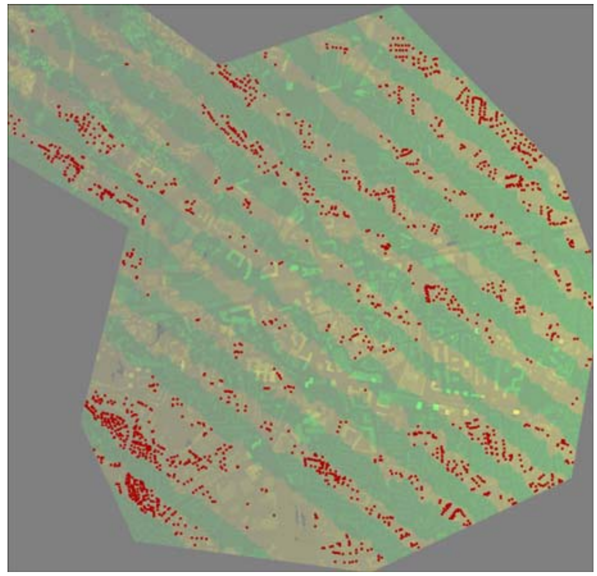


Figure 5: Distribution of 2043 roof measurements in the Enschede dataset.

Strip 1	Strip 2	Flight direct.	# Roofs	Δx (cm)	Δy (cm)	RMS (cm)	StDev (cm)
17	19	P	165	-2.1	0.7	3.2	2.9
19	16	P	126	3.7	-3.0	4.8	3.4
16	18	O	78	1.7	8.1	6.2	3.0
18	15	P	150	-2.0	-0.8	3.5	3.1
15	13	P	182	1.7	-2.2	3.5	2.8
13	10	P	75	3.3	-2.6	4.3	2.9
10	7	O	228	0.2	-9.6	7.2	2.8
7	4	P	211	2.7	-1.8	4.0	3.3
4	14	P	129	3.9	-1.4	4.5	3.5
14	12	P	128	-0.7	-2.5	3.3	2.8
12	9	P	54	2.1	-2.8	3.8	2.8
9	8	O	188	0.1	8.8	6.9	2.6
8	5	P	180	2.7	-2.9	4.2	3.1
5	1	P	149	-2.0	-0.5	2.5	2.1

Table 4: Offsets and accuracies of the Enschede dataset with relative flight directions (parallel (P) / opposite (O)).

Inspection of the flight directions revealed that these three strip pairs consisted of strips with flight lines in opposite directions whereas all other strips pairs had the same flight direction. The offsets between the strip pairs with opposite flight directions are about 8-9 cm. Most likely all strips were shifted by some 4-4.5 cm due to a small calibration error (in addition to other even smaller systematic offsets). At a flight height of 275 m this could e.g. have been caused by a boresight misalignment of 0.009 degree.

For every set of five nearby ridge lines, local offset have been computed to investigate drifts in the platform positioning. Fig. 6 shows the offset vectors at the point of gravity of the ridge lines used for the offset computation. Local offsets ranged up to 14 cm. In general, the offset vectors have similar sizes and directions throughout a strip overlap. In some strip overlaps systematic changes can be observed. E.g. in the second overlap in the northeast corner, offsets are clearly larger in the east part of the overlap.

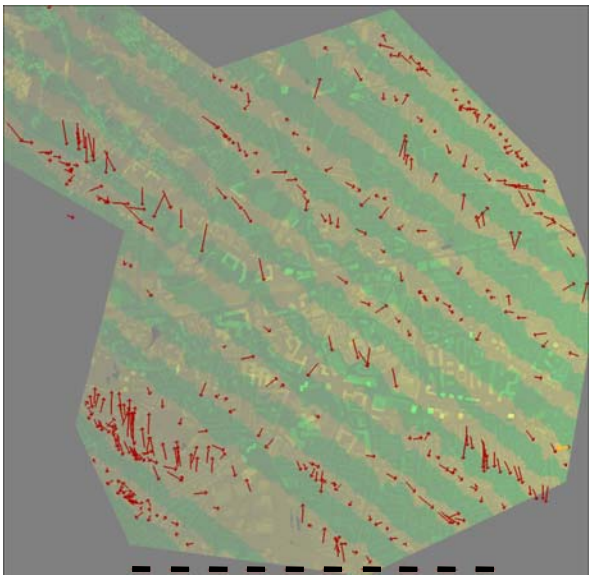


Figure 6: Displacement vectors in Enschede dataset. The black dashes at the bottom of the figure correspond to 100 m in terrain and 10 cm in offset vector scale.

After correction for the global strip offsets (i.e. neglecting the drifts), standard deviations of the differences between the ridge lines have been computed (Table 4). These standard deviations are consistently low with an average of 3.0 cm. These values include both the random positioning errors as well as the non-constant components of systematic errors. Considering that the values are standard deviations of position differences, it can be concluded that the standard deviation of the combined random and non-constant systematic errors in the X- and Y-coordinates is about 2.1 cm. This demonstrates the low noise level of platform positioning with the configuration of two receivers on board of the platform and multiple reference stations.

5. CONCLUSIONS

In the presented research it was shown that the planimetric accuracy of laser scanning surveys can be assessed largely automatically by extracting and comparing ridge lines in overlapping strips. The whole process can run as a batch job and only required smaller checks to eliminate incorrectly extracted ridge lines.

In the three examined blocks offsets between strips proved to have a large constant component. Hence, a simple translation of strips could already significantly improve the planimetric accuracy of the point clouds.

The analysis of the dataset of Enschede demonstrated the high accuracy that can be obtained in platform positioning. With a little additional calibration, offsets between strips could be reduced to a maximum of 3-4 cm. Planimetric standard deviations of 2 cm have been achieved.

These estimated offsets as well as the standard deviation of remaining planimetric errors can be combined with the point density to derive the measures for the quality of cartographic features like building outlines extracted from point clouds. With the high point density datasets that currently become available it is expected that point clouds will not just be the main data source for producing digital elevation models, but also become of increasing importance for semi-automated mapping and map updating.

In addition to what was demonstrated in this paper, the extracted ridge lines can also be used for the determination of the height accuracy. If planimetric accuracy is of no concern, height accuracy may, however, be faster analysed by selecting horizontal patches in the strip overlaps (Crombaghs et al., 2000, 2002).

Furthermore, the ridge line pairs could also serve as input to a strip adjustment procedure to remove both planimetric and height errors in the strips. While the basic observation in this adjustment is the distance between surfaces (Friess, 2006), the usage of line pairs easily allows to distinguish between planimetric and height accuracy.

ACKNOWLEDGEMENTS

The Brabant dataset was kindly provided by the Directorate-General of Public Works and Water Management (Rijkswaterstaat). The Zeeland dataset was kindly provided by AHN steering committee.

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