PRECISE QUALITY CONTROL OF LIDAR STRIPS

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ABSTRACT

LiDAR systems have been established as technology for fast and high-resolution acquisition of 3D point clouds. In general, LiDAR data acquisition is conducted by private companies who are also responsible for processing and quality control. However, in many cases a subsequent quality assessment of overlapping LiDAR strips still reveals apparent horizontal and vertical offsets which are caused by undetected systematic errors (e.g. insufficient calibration and strip adjustment). The presented work covers methods for the detection of remaining discrepancies in overlapping LiDAR strips with main focus on the development of a new precise 3D measurement technique based on intersecting roof ridge lines and roof planes which are automatically reconstructed from the LiDAR point clouds in overlapping strips. The coordinate differences between conjugate intersection points are incorporated in an adjustment process to resolve for the residual errors of each LiDAR strip separately. The new 3D reconstruction method can also take advantage of full waveform measurements like pulse width and intensity which are decomposed from the waveforms. Finally, the LiDAR strips are corrected and validated by checking the correspondence among neighbouring strips. The quality control system has been successfully applied to pre-processed and adjusted LiDAR strips. In general, the results show that significant discrepancies mainly in position still exist. After the adjustment of 6 strips (altitude 1000 m) using precise 3D measurements, the relative horizontal displacements between adjacent strips are improved by more than 60 %.

INTRODUCTION

Geospatial databases are essential for describing the Earth’s surface with the requirement of high quality and being up-to-date. LiDAR, also known as airborne laser scanning (ALS) has been established as technology for fast and high-resolution acquisition of the terrain surface. Major secondary products of LiDAR data are DTMs and DSMs for various applications in geoscience. Due to the rapidly increasing amount of LiDAR data in the recent years, the users were increasingly faced with the cost-intensive collection, continuation and quality assessment of geospatial databases. The dominant sources affecting the quality of LiDAR derived products are residual errors coming from insufficient calibration and strip adjustment, and errors in data classification and filtering.

In this paper, one focus is on the detection of horizontal and vertical discrepancies between overlapping areas of adjacent LiDAR strips. Absolute measurements are acquired for control elements, e.g. plane areas or independently measured objects which can be recovered by the LiDAR data. Relative displacements are measured for tie elements, viz. corresponding objects which can be clearly reconstructed from the laser point clouds in overlapping strips. These displacements (mainly caused by residual systematic errors concerning the laser range measurement, GPS position, IMU attitudes and the alignment of the LiDAR system components) serve as preliminary quality control. The relation of measured horizontal and vertical offsets and residual errors is modelled by a mathematical equation. By introducing the offset measurements as observations, the residual errors are resolved by means of an adjustment approach and finally, the resulting corrections are applied to the laser points.

In most cases, LiDAR data acquisition is conducted by private companies who also perform the pre-processing of the laser points, the classification and the quality control. Nevertheless, subsequent quality investigations still exhibit horizontal and vertical offsets which are clearly visible at distinct objects (e.g. roof profiles) in overlapping areas of adjacent tracks (Figure 3). The data delivered to the end-user often consists of the bare 3D laser point coordinates, the laser intensity and a point class labelling. However, system parameters like GPS positions and IMU rotations are not provided.

The validity of the measured horizontal and vertical offsets depends on the use of adequate measuring techniques. In the literature various methods can be found for it. Due to the fact that the direct comparison of
measured laser points from different LiDAR tracks is not possible, selected surfaces reconstructed from the laser point clouds are considered. Whereas vertical offsets are detected by comparing plain areas, the measurement of relative and absolute horizontal shifts is based on different approaches.

Kilian et al. (1996) are using ground planes of buildings for measuring building corners and the corresponding corner coordinates from the laser data. Two methods for detecting offset values are based on a TIN structure deduced from the laser points. Burman (2002) derives the height discrepancy for a laser point of the first strip by relating the position to the TIN surface of the second strip by means of linear interpolation of the three surrounding nodes. Maas (2002) is generating local TINs for small areas in overlapping strips and derives 3D offsets through a least squares matching between the selected subsets. The disadvantage of this method is that occluded areas caused e.g. by trees and buildings must not be matched. For the detection and exclusion of occluded areas from the laser points, further thorough and elaborate analyses are inevitable. For both approaches the laser reflectance (intensity) discrepancies were also included serving as a helpful tool in regions with low height variations but good intensity contrast. Vosselman (2002) has shown that reflectance data at edge locations may be suitable for the derivation of horizontal offsets. However, only long edges should be incorporated to avoid inaccurate results due to the prevalent noise.

The focus in Filin (2003), Filin and Vosselman (2004), Pfeifer et al. (2005) and Friess (2006) is on the extraction of suitable planar segments for the determination of corresponding tie and control elements in different LiDAR strips. Natural or man-made surfaces are used. Filin (2003) emphasizes that the error recovery can benefit from object surfaces with different slopes. Pfeifer et al. (2005) recommend several selection criteria, e.g. to constrain the segment size, the surface shapes and orientations, and the distance between surface elements, leading to at least 20 corresponding segments per overlay. Finally, the offsets are determined by comparing the barycenters of the selected surfaces. However, the localization of the barycenters depends on the laser point coverage representing the tie surfaces.

In the recent years, the emphasis was more on the extraction of building roof shapes as tie elements. The fully 3D adjustment approach of Kager (2004) for correction of exterior (GPS, IMU) and interior (boresight) orientation elements incorporates artificially tie points resulting from intersection of planar roof elements. Although describing a simultaneous 3D adjustment approach, the effect of the post-correction was only demonstrated for the height differences. Pothou et al. (2008) conduct the estimation of boresight misalignment parameters by comparing LiDAR derived roof surfaces with photogrammetrically reconstructed reference surfaces.

An extension with respect to these approaches is the addition of extracted roof ridge lines from roof plane intersections. Ahokas et al. (2004) are using ridge lines for a comparison study with repeated ALS observations. Schenk et al. (1999) present a quality accuracy study for LiDAR data in an urban area by comparing reconstructed roof ridge lines after laser point segmentation with photogrammetric DEM measurements and directly measured roof ridge points. Habib et al. (2008) are computing corresponding linear features from intersections of roof planes in overlapping LiDAR strips. The linear features are represented by its end points and their coordinate discrepancies between different strips serve as input for a strip adjustment and quality control. The variance of the utilized line end points is artificially expanded in line direction to compensate for the fact that the points along corresponding lines are not conjugate. Vosselman (2008) presents a largely automatic procedure for assessing the planimetric accuracy of three LiDAR surveys in the Netherlands. Relative horizontal shifts between overlapping areas of adjacent strips are measured by detection and comparison of reconstructed roof ridge lines from the laser data. In this approach, the center points of corresponding ridge lines are derived. Herein, the weakness of this method can be found. Because the laser point clouds of different strips are not describing the same roof outline, the lengths of reconstructed roof ridge lines will differ resulting in misleading positions of line centers. The impact is worsened if e.g. the laser points in one strip only cover parts of the roof with respect to the other strip.

The main focus of the presented work is on the development of a new method for the precise 3D measurement of remaining offsets in overlapping laser scanning strips. For this purpose, appropriate roof shapes with crossing ridge lines are reconstructed from the laser point clouds. Then, 2D and 3D points are derived by intersecting the roof planes and ridge lines for each strip separately. The approach is basically suitable for full waveform data comprising the pulse energy (viz. the intensity) and the pulse width as additional laser point attributes. The coordinate differences achieved from this and other measuring methods deliver the desired discrepancies which are incorporated in a least squares adjustment process to resolve for residual errors for shifts and rotations. After application of the corrections, the horizontal offsets could significantly be reduced for a test area including 6 adjacent laser strips.
METHODS

Concept

LiDAR surveys are usually conducted by scanning the terrain surface in a strip-wise manner with an across-track overlap of 30%. There are three types of error sources affecting the acquired laser point coordinates, unsystematic gross errors (blunders), systematic errors and random errors (noise). Whereas gross errors are mostly discarded within the pre-processing of laser measurements, random errors coming from instrument noise will always remain (Friess, 2006). Thus, for a mathematical formulation, the measured discrepancies between overlapping areas of adjacent strips are exclusively related to systematic residual errors caused by insufficient calibration of the LiDAR system components or inadequate strip adjustment.

Comprehensive mathematical formulations for the relationship between observed laser point coordinates and system-dependent parameters are given by various authors (Kilian et al. 1996; Burman, 2002; Schenk, 2001; Filin, 2003). Due to the strip-wise acquisition of LiDAR surveys, the systematic errors are supposed to affect the coordinate offsets for each strip separately. For simplification, some assumptions are defined for the mathematical model (Eq. 1). First, time dependent portions are not considered. The rotation angles (roll and heading) are assumed as small values and no rotation angle along the y-axis of a strip $i$ is applied. This means that we do not compensate for a pitch angle error which causes essentially a horizontal shift in the laser points. The error model resp. the observation equations are established in a local strip coordinate system in which the strip centroids represent the origin and the local x-axis is approximately aligned to the flight direction (Vosselman and Maas, 2001).

![Figure 1. Sample configuration of LiDAR strips with control (green) and tie elements (orange). As example, relative horizontal offsets $\Delta X'$ and $\Delta Y'$ between overlapping strips are measured for a tie element (violet).](image)

$$\begin{bmatrix} X_{ik}' \\ Y_{ik}' \\ Z_{ik}' \end{bmatrix} = \begin{bmatrix} 1 & -\Delta h_i & 0 \\ \Delta h_i & 1 & -\Delta r_i \\ 0 & \Delta r_i & 1 \end{bmatrix} \begin{bmatrix} x_{ik} - x_i' \\ y_{ik} - y_i' \\ z_{ik} - z_i' \end{bmatrix} + \begin{bmatrix} X_{0i} \\ Y_{0i} \\ Z_{0i} \end{bmatrix}$$

(1)

where

$X_{ik}', Y_{ik}', Z_{ik}'$ Coordinates of a laser point $k$ of the corrected strip $i$

$\Delta r_i, \Delta h_i$ Rotation angles for roll and heading of strip $i$

$x_{ik}, y_{ik}, z_{ik}$ Coordinates of a laser point $k$ in the uncorrected strip $i$

$X_{0i}, Y_{0i}, Z_{0i}$ Shifts of the uncorrected laser strip $i$

$x_i', y_i', z_i'$ Centroid of uncorrected strip $i$
The unknown parameters of each strip $i$ are found in a combined adjustment using control and tie elements. Control and tie elements are usually horizontal, vertical or 3D elements measured by an appropriate measurement technique.

**Measurement Techniques**

There are three implemented methods to derive spatial offsets between overlapping laser strips. The first two of them are well-known and are only described in brief. Main interest is given on the third approach concerning the precise measurements of 3D offsets between neighbouring laser strips.

**Vertical offsets.** The first algorithm is dedicated to vertical measurements, on the one hand absolute measurements of height control features and, on the other hand, relative height discrepancies between LiDAR strips. In case of a height control element, for example a soccer field or flat roof, the mean height of laser points with respect to the grid defined by the single height posts of the control element is calculated. For the measurements of relative height displacements, almost flat areas are searched by masking the areas which exceed a predefined terrain slope. The slope information is derived from a low resolution reference DTM. If an appropriate plane area (with no objects and vegetation) was found, a high-resolution DTM is calculated from the selected points of the first strip and serving as height reference (tie feature) for the laser points of the second strip. The measured vertical offset is resulting from the mean of the vertical offsets of all laser points from the second track with respect to the ‘reference’.

**Horizontal offsets.** The second algorithm is designed to derive horizontal offsets. For this purpose, non-vegetated tilted surfaces are considered. Like in the first algorithm, a high-resolution DTM is derived from the points of the first strip representing the reference surface (tie feature). Now, the height values of the other strips are compared with this surface leading to certain mean height displacements and standard deviations. Then, the point clouds of the other strips are slightly moved horizontally, and the comparisons are performed again. This in turn results in values for mean height displacements and standard deviations. This process is repeated until the standard deviations of the height displacements reach an absolute minimum, and finally, the corresponding horizontal offsets (easting, northing) are registered.

**3D Measurement Technique ‘Roof Shapes’.** A new method has been developed to derive 2D as well as 3D points from the intersection of modelled roof ridge lines coming from different laser tracks. The main processing steps are applied to each LiDAR strip and can be divided as follows: (1) Selection of appropriate roof surfaces, e.g. L-shaped or T-shaped. (2) Separation of roof points from bare Earth points. Herein, the separation is supported by predetermined building outlines or, if not available, by dividing the points according to their pre-classified point class and height values. (3) Computation of geometric and physical laser point features (Figure 2a and 2b). Note that the features intensity and pulse width are optional and are dedicated to full waveform LiDAR systems. They can be calculated via a waveform decomposition (Reitberger et al., 2008). At each laser point location, a local fitting RANSAC plane is computed from the surrounding points. According to the given point density, an appropriate search radius is determined to ensure that a predefined number of points is included. Laser points for which the height variations with respect to the local plane exceed a defined threshold (this appears for example for points on a roof ridge) are rejected. Afterwards, for each selected laser point, a list of features is determined: The xyz-components of the plane normal vector $n_x$, $n_y$ and $n_z$, the orientation of the roof plane $p_o=\arctan(n_x/n_y)$, the laser intensity and the pulse width in case of full waveform laser data. (4) Segmentation of roof planes by means of clustering using the derived features (Figure 2c). A preliminary clustering of laser points is performed by means of the k-means algorithm and a given number of clusters. For each of the found clusters, common features as described before are derived and assigned. Tiny clusters with a very small number of points (e.g. 5) are apparently discarded. Then, the clusters undergo a hierarchical clustering which leads to a merging of clusters with nearly coinciding features and resulting to clearly separated roof planes. (5) Finally, an adjusting plane is computed including all laser points from each merged cluster. Laser points on small features like chimneys or dormers are detected by means of their distance to the adjusting plane and are filtered out (Figure 2d). (6) Evaluation of roof ridge lines by means of plane intersections. The appropriate roof planes which are used for plane intersection are selected according to their features (e.g. opposite orientation) and are intersected, leading to a pair of ridge lines in the normal case (Figure 2e). (7) Derivation of 2D points from line intersections and 3D points from plane-line intersection. Because the extracted ridge lines are representing skewed straight lines in space, a 3D intersection between them could not be carried out. However, a 2D intersection is always feasible meaning that the X- and Y-coordination of a ridge line intersection are always ascertained. Fully 3D coordinates can be achieved by intersecting the lower of the two ridge lines with the contrary roof planes, resulting in two intersection points (Figure 2f). (8) Finally, the coordinate differences of conjugate intersection points in overlapping strip areas can be calculated, revealing the spatial offsets caused by remaining shifts and rotations (Figure 2g).
Derivation of the plane normal

Normal vector component $n_x$

Normal vector component $n_y$

Normal vector component $n_z$

Plane orientation $po$

Figure 2a. Geometrical laser point features.

Laser intensity

Pulse width

Figure 2b. Optional laser point features calculated from full waveform data.

Figure 2c. Preliminary plane clustering containing chimneys and dormers.

Figure 2d. Post-edited plane segments cleaned from chimneys and dormers.

Figure 2e. Intersection of plane segments.

Figure 2f. Calculation of 2D and 3D intersection points.

Figure 2g. Determination of 2D and 3D offsets.

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Sensitivity analysis. The internal accuracy of the measured offsets is determined by means of repeating the entire measurement process (steps 4-8) for a predefined number of runs (e.g. 20). The standard deviations are caused by variations coming from the random selection of laser points in the RANSAC-based plane adjustment (step 5). Thus, a statistical analysis is performed leading to a mean value (the offset measurement) and its standard deviation. In addition, within this analysis, outliers are detected and removed according to a 2-sigma criterion.

Correlation analysis. The choice of the laser point features has an impact on the preliminary plane clustering, and in the following on the separation of the roof planes. In most cases, the features describing the geometric properties (xyz-components of the plane normal $n_x$, $n_y$, and $n_z$, plane orientation $p_o$) are sufficient for the reconstruction process. In case that full waveform data are processed, also the physical laser point features, e.g. the laser intensity and the pulse width which are calculated via a waveform decomposition can be incorporated. However, as displayed in Figure 2b it is obvious that the physical laser point features are afflicted with higher noise. In order to deal with this condition and to avoid manual interaction, an automatic selection of laser point features was established by means of a correlation analysis which guarantees that the selected features ensure the highest possible confidence level concerning the segmentation of the laser points. As initial step of the correlation analysis, a preliminary plane separation is performed with all laser point features as described before. Now, the correlation coefficients are computed for all laser point features and for all points which were segmented before, namely with each combination of roof plane pairs, and averaged afterwards. Then, the mean of all correlation coefficients is compared with a threshold, e.g. 0.98. If the mean correlation coefficient meets the threshold, all chosen laser point features are used for the further processing. In the other case, the lowest correlation coefficient is depicted and the corresponding laser point feature is discarded. In the following, the correlation analysis is repeated until at least the criterion is fulfilled, or at least two laser point features remain. It this context it must be noted that the plane orientation is always fixed within this investigation, cause this laser point feature has the strongest relation to the preliminary segmented roof planes.

Quality control. In many cases, the quality control in the framework of LiDAR surveys is limited to a visual inspection of adjacent laser strips in overlapping areas, e.g. by overlaying the laser point profiles of roofs or other appropriate objects. In addition, the quality assessment relies on a high extent on the personal point of view of the operator. With the proposed measurement techniques, the measured horizontal and vertical offsets now can be used for a numeric based quality control and are supporting the results from the visual control (Figure 3). Moreover, the results are achieved by well-defined algorithms, transparent and the basis for further processes.

![Figure 3. Large planimetric discrepancies measured at a roof showing insufficient strip adjustment.](image)

Strip Adjustment

For this purpose, two basic types of observation equations are established. Equation (2) stands for an absolute measurement for a control element, equation (3) for a relative measurement between overlapping strips and are given as follows

\[
\begin{bmatrix}
X_a \\
Y_a \\
Z_a
\end{bmatrix} +
\begin{bmatrix}
v_X \\
v_Y \\
v_Z
\end{bmatrix} =
\begin{bmatrix}
1 & -\Delta h & 0 \\
\Delta h & 1 & -\Delta h \\
0 & \Delta r & 1
\end{bmatrix}
\begin{bmatrix}
x_a - x' \\
y_a - y' \\
z_a - z'
\end{bmatrix} +
\begin{bmatrix}
X_m \\
Y_m \\
Z_m
\end{bmatrix}
\]

Equation (2)
\[
\begin{pmatrix}
\Delta x_{ik}' \\
\Delta y_{jk}' \\
\Delta z_{ik}'
\end{pmatrix}
+ \begin{pmatrix}
v_{AX} \\
v_{AY} \\
v_{AZ}
\end{pmatrix}
= \begin{pmatrix}
I & -\Delta t_i & 0 \\
0 & 1 & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
x_{ik}' \\
y_{ik}' \\
z_{ik}'
\end{pmatrix}
- \begin{pmatrix}
I & -\Delta t_j & 0 \\
0 & 1 & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
x_{jk}' \\
y_{jk}' \\
z_{jk}'
\end{pmatrix}
+ \begin{pmatrix}
X_0 - X_0 \\
Y_0 - Y_0 \\
Z_0 - Z_0
\end{pmatrix}
\] (3)

where

\[X_{ik}', Y_{ik}', Z_{ik}'\] Measurements on a control element \(k\) in the strip \(i\)

\[\Delta X_{ik}', \Delta Y_{jk}', \Delta Z_{ik}'\] Offset measurements between strip \(i\) and \(j\) on a tie element \(k\)

\[v_{\Delta x}, v_{\Delta y}, v_{\Delta z}\] Residuals of the measurements on a control element

\[v_{\Delta x}, v_{\Delta y}, v_{\Delta z}\] Residuals of the measurements on a tie element

\[X_0, Y_0, Z_0\] Unknown shifts of strip \(i\)

\[\Delta t_i, \Delta t_j\] Unknown rotation angles (compensate IMU rotations roll and heading) for the strip \(i\)

\[x_i^S, y_i^S, z_i^S\] Strip centroid (Calculated from laser points of uncorrected strip)

For the strip adjustment, 6 different observation types are introduced; type 1-3 belonging to observation equation (2), type 4-6 to equation (3) (Table 1).

**Table 1. Observation types used within strip adjustment**

<table>
<thead>
<tr>
<th>Obs. Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Absolute vertical measurement with respect to a height control element (e.g. soccer field)</td>
</tr>
<tr>
<td>2</td>
<td>Absolute horizontal measurements with respect to a control element</td>
</tr>
<tr>
<td>3</td>
<td>Absolute 3D measurements with respect to a control element</td>
</tr>
<tr>
<td>4</td>
<td>Relative vertical offset measurement between adjacent strips for a tie element</td>
</tr>
<tr>
<td>5</td>
<td>Relative horizontal offset measurement between adjacent strips for a tie element</td>
</tr>
<tr>
<td>6</td>
<td>Relative 3D offset measurement between adjacent strips for a tie element</td>
</tr>
</tbody>
</table>

For the stochastic model, each of the observations types can be assigned with individual a-priori standard deviations reflecting their varying accuracy levels. After the strip adjustment, the comparison of the a-posteriori standard deviations for each separate observation with their a-priori values reflects the accuracy of the group specific measurements.

**DATASET**

The algorithms are evaluated for 6 sample adjacent LiDAR strips within a project area ‘ALS Bayern/Kempten’ located in Southern Bavaria and surveyed in May 2006 (Figure 4).
For more than a decade, the Bavarian Office for Surveying and Geographic Information (LVG) systematically produces and delivers high-resolution DTMs with down to 1-m spacing based on airborne laser scanning. The flight surveys are conducted by several companies who are also responsible for pre-processing, georeferencing of the laser points, adjustment of the laser strips and an automatic classification of the raw laser data. Moreover, an internal quality control is performed by these contractors. Laser point clouds for first and last pulse are then delivered to the LVG. The datasets itself contain the UTM coordinates, the ellipsoidal height above GRS80, the point class derived by the flight company and the laser intensity. However, information on GPS positions and IMU attitudes are not available.

The entire project area was flown in a strip wise manner, mostly in east-west direction except two sections which were registered in north-south and, containing the sample strips, around 30 degrees rotated against east-west. For each subarea, an additional cross strip was appended. With a predefined flight altitude of 1000 m and a scan angle of 22 degrees, this led to a strip width of around 800 m. 45 % were chosen as across-track overlap resulting in approximately 300 m wide common areas of neighbouring strips. The mean point density is about 1-2 points/m².

For the generation of 2D and 3D control points, several roof ridge lines were determined photogrammetrically by measuring sample roof ridge points in digitized aerial images with nearly the same acquisition date as the LiDAR data. Based on the image scale of 1:12400 and the pixel size of 14 μm, the measurement accuracy in the stereo model can be estimated to 17.5 cm for the planimetric and 35 cm for the height coordinates. 2D points are derived by intersecting the reconstructed ridge lines in the horizontal projection. Virtual 3D points are constructed by taking the 2D point coordinates and deriving the Z-coordinate by means of intersecting the orthogonal plane through the 2D point with the lower ridge line.

EXPERIMENTS

Adjustment Results

As mentioned before, the mathematical model is designed to resolve for 3 shifts and the 2 rotations compensation the IMU rotations for roll and heading for each individual strip. Optionally, the model is also capable to determine the 3 shifts and 2 rotations separately. Thus, for a pair of adjacent strips, 10 unknowns have to be resolved and 5 unknowns more for each additional strip. Figure 4 also displays the locations of all tie and control elements. The blue squares are representing tie elements with vertical offset measurements, the red ones the locations with 2D and 3D offset measurements. The red triangles stand for 2D and 3D measurements for control elements which are necessary for the absolute alignment of the LiDAR strips.

The adjustment process was performed according to the mathematical model given by equations (2) and (3) using overall 190 observations for observation types 2-6 (observation type 1 was not included due to missing height control area within the test site) to resolve for the overall 18 unknown shifts and 12 unknown rotations. As mentioned before, the different observation types have to be handled individually concerning their internal accuracy and as consequence the a-priori standard deviations which are incorporated into the stochastic model. The internal standard deviations of the sensitivity analysis for the offsets using the 3D measurement technique ‘roof shapes’ are mostly below a 3 cm level (Figure 5).

![Figure 5](image-url) Internal standard deviations of planimetric (green) and height (cyan) offsets using the 3D measurement technique ‘roof shapes’. The red line denotes the 3 cm level.
However, several tests have shown that the assumption using these internal standard deviations as a-priori input were too optimistic. Therefore, more appropriate values were defined for the a-priori standard deviations for each observation type leading to more reasonable results (Table 2). The comparison of the standard deviation before strip adjustment (sigma a-priori) and after strip adjustment (sigma a-posteriori) for the individual observation types reflects the particular accuracy level.

**Table 2. Standard deviations before and after strip adjustment for each observation type separately**

<table>
<thead>
<tr>
<th>Obs. Type</th>
<th>sigma a-priori [cm]</th>
<th>sigma a-posteriori [cm]</th>
<th># observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>not resolved</td>
<td>not resolved</td>
<td>not resolved</td>
</tr>
<tr>
<td>2</td>
<td>16.5</td>
<td>15.4</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>17.7 (planimetry), 12.0 (height)</td>
<td>16.6 (planimetry), 11.0 (height)</td>
<td>30</td>
</tr>
<tr>
<td>4</td>
<td>7.5</td>
<td>7.6</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>9.5</td>
<td>7.8</td>
<td>34</td>
</tr>
<tr>
<td>6</td>
<td>9.5 (planimetry), 7.0 (height)</td>
<td>9.7 (planimetry), 6.5 (height)</td>
<td>117</td>
</tr>
</tbody>
</table>

The resolved unknowns and their standard deviations for the 6 adjacent strips of the test site are listed in Table 3.

**Table 3. Resolved shifts and rotation angles**

<table>
<thead>
<tr>
<th>Strip</th>
<th>$X_0$ [cm]</th>
<th>$\sigma X_0$ [cm]</th>
<th>$Y_0$ [cm]</th>
<th>$\sigma Y_0$ [cm]</th>
<th>$Z_0$ [cm]</th>
<th>$\sigma Z_0$ [cm]</th>
<th>$\Delta r$ [deg]</th>
<th>$\sigma \Delta r$ [deg]</th>
<th>$\Delta h$ [deg]</th>
<th>$\sigma \Delta h$ [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>160</td>
<td>61.4</td>
<td>6.7</td>
<td>20.1</td>
<td>7.2</td>
<td>19.9</td>
<td>5.4</td>
<td>0.001</td>
<td>0.002</td>
<td>-0.002</td>
<td>0.001</td>
</tr>
<tr>
<td>161</td>
<td>27.8</td>
<td>6.1</td>
<td>30.7</td>
<td>6.3</td>
<td>14.4</td>
<td>4.7</td>
<td>0.002</td>
<td>0.002</td>
<td>-0.002</td>
<td>0.001</td>
</tr>
<tr>
<td>162</td>
<td>21.0</td>
<td>5.6</td>
<td>-16.7</td>
<td>5.8</td>
<td>-0.6</td>
<td>4.4</td>
<td>-0.005</td>
<td>0.002</td>
<td>-0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>163</td>
<td>-5.9</td>
<td>5.6</td>
<td>-1.6</td>
<td>5.8</td>
<td>-5.3</td>
<td>4.9</td>
<td>-0.005</td>
<td>0.002</td>
<td>-0.002</td>
<td>0.001</td>
</tr>
<tr>
<td>164</td>
<td>-12.3</td>
<td>7.1</td>
<td>-26.9</td>
<td>12.9</td>
<td>-3.1</td>
<td>7.5</td>
<td>-0.007</td>
<td>0.003</td>
<td>-0.006</td>
<td>0.002</td>
</tr>
<tr>
<td>166</td>
<td>-47.5</td>
<td>7.4</td>
<td>-9.0</td>
<td>14.3</td>
<td>-1.4</td>
<td>7.9</td>
<td>-0.008</td>
<td>0.003</td>
<td>-0.005</td>
<td>0.002</td>
</tr>
</tbody>
</table>

**Strip Correction and Validation**

The corrections were applied as follows: For each LiDAR strip of the test site, the flight trajectory is available including the 1-s GPS positions, the date and time and the GDOP (global dilution of precision). For each laser point location, the measurement constellation is reconstructed by calculating the orthogonal plane of the trajectory including the uncorrected laser point. Then, the derived shifts and rotations resulting from the adjustment are applied for the laser points of each LiDAR strip separately. Finally, the 3D measurement technique is carried out for the corrected laser points revealing that the relative displacements between adjacent strips could be reduced significantly, which is demonstrated by visual (see Figure 6) and numeric control (see Table 4). Note that the improvement in $\Delta X', \Delta Y'$ and $\Delta Z'$ after the strip adjustment are fully consistent with relevant strip displacements $X_0, Y_0, Z_0$ ($i=160,161$).

**Figure 6. Relative displacements between strip 160 (blue) and 161(red) before and after strip adjustment.**

**Table 4. Relative displacements of 25 tie elements before and after strip adjustment.**

<table>
<thead>
<tr>
<th></th>
<th>r.m.s. planimetry [cm]</th>
<th>r.m.s. height [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>before strip adjustment</td>
<td>32.5</td>
<td>6.4</td>
</tr>
<tr>
<td>after strip adjustment</td>
<td>11.7</td>
<td>6.9</td>
</tr>
</tbody>
</table>
DISCUSSION

The main focus of the present work is on a new and precise 3D measurement technique for the determination of horizontal and vertical offsets between overlapping regions of adjacent LiDAR strips. The discrepancies can be measured using the intersection points of reconstructed roof ridge lines and roof planes. Table 2 shows that the estimated accuracy of the method after the strip adjustment is on a high level with standard deviations of 8 – 10 cm in planimetry and 7 cm in height for the relative displacement measurements. The control points show the standard deviations that are roughly worse by the factor 2. This can be mostly attributed to unresolved systematic errors in the photogrammetric stereo models which reduce the absolute measuring accuracy. Furthermore, the r.m.s. displacements after the strip adjustment in table 4 match excellently the estimated accuracy showing the appropriate correction of the laser points with the adjusted strip parameters. Interestingly, the estimated accuracy is roughly by the factor 2 worse than the precision of the new measurement technique (see figure 5). This disagreement can be explained on the one hand by a non-perfect tie element configuration causing a weak adjustment result. On the other hand, non-linear strip deformations caused by, for instance, non-adequate IMU measurements during jerky platform movements or uncalibrated non-linear scan angle errors might not sufficiently be modelled by the mathematical model (Eq. 1). Similar effects could be observed by Vosselman and Maas (2001) and Maas (2002) who report on a precision of the applied TIN least-squares matching of 10 cm and estimated standard deviations after the strip adjustment (Block Eelde) of 25 cm in planimetry and 8.5 cm in height. Moreover, the proposed approach is independent of the roof area covered by the laser points from different flyovers. This is an advantage with respect to the methods described by other authors (Pfeifer et al., 2005; Vosselman, 2008) which rely on the area size of tie surfaces when calculating their barycenters, resp. on the length of ridge lines when calculating their center points.

The measured offsets are incorporated in a strip adjustment approach to resolve for remaining shifts and rotations between LiDAR strips. The horizontal shifts of about 60 cm and vertical shifts of about 20 cm are resolvable for the already pre-adjusted LiDAR strips. Filin and Vosselman (2004) have detected comparable horizontal offsets by analysing 10 parallel and 10 crossing strips. The resolved rotations are marginal with respect to the derived shifts, leading to the assumption discovered by Vosselman (2008) that “a simple translation of strips could already significantly improve the planimetric accuracy of the point clouds”.

Furthermore, it is evident that horizontal discrepancies between the LiDAR strips are significantly improved by 64% by correcting the strips with the adjusted strip parameters. No improvement is achieved for the vertical discrepancies which are below 7 cm anyway before the adjustment. The results are comparable to the findings from Vosselman and Maas (2001), in which the degree of improvement was around 40% for the horizontal discrepancies.

CONCLUSIONS

LiDAR has established as appropriate technique for the 3D acquisition of the Earth surface with the ability of high resolution and accuracy. LiDAR-derived secondary products like DTMs and DSMs serve as application in various fields of geoscience. However, the demands on quality are also rising and thus the accuracy of the LiDAR data has to meet the challenge. Inadequate system calibration, insufficient strip adjustment and errors concerning the data filtering are the main sources affecting the quality of LiDAR products and which are recognized by means of discrepancies in the common areas of neighbouring LiDAR strips.

The experiments based on 6 adjacent LiDAR strips from a test site in Southern Bavaria have pointed out that significant discrepancies still exist between individual strips. These offsets can be detected by visual inspections, a common but cost-intensive and time-consuming practice often performed by end-users like survey administrations. With a new 3D measurement technique based on reconstructed roof shapes and roof ridge lines, remaining horizontal and vertical discrepancies between LiDAR strips now can be precisely detected with an accuracy of 8-10 cm for planimetry and 7 cm for the height, thus serving as a helpful tool for a comprehensive quality control. In addition, the measurements can be incorporated as observations in a subsequent strip adjustment to resolve systematic residual errors that are responsible for the detected shifts. After the application of the corrections to each strip separately, the efficiency can be controlled using again the proposed 3D measurement technique. In this context it has to be noted, that the data set used for the investigation was already adjusted by the data provider.

Nevertheless, there are several options for future work. The measurement methods could be optimized by more automation. Investigations should also focus on an optimal configuration of tie elements. In addition, other measurement methods are worth to be evaluated for application (e.g. using straight lines or planes as control or tie elements).
REFERENCES


