# AUTOMATIC TIE ELEMENTS DETECTION FOR LASER SCANNER STRIP ADJUSTMENT

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**KEY WORDS:** airborne laser scanning, segmentation, strip adjustment

**ABSTRACT:**
Measurements with airborne laser scanners are performed in strips, usually with multiple length strips and a few cross strips. Due to i) wrong or inaccurate calibration of the entire measurement system and due to ii) the limited accuracy of the exterior orientation determination with GPS and IMU and systematic errors of these devices, adjacent strips can show discrepancies in their overlap. For removing these discrepancies strip adjustment algorithms require quantification on these offsets at various locations within the overlapping zones. We present a general method for determining these discrepancies automatically based on segmentation of the overlap. A method to determine the accuracy of these discrepancy observations is demonstrated as well. In the examples we reconstruct mean offsets between neighbouring strips of a few centimetres, which, also show substantial variation along the strip axis. The accuracy of this discrepancy observations is in the order of 2cm. The method developed for discrepancy determination can be applied to height or full 3D strip adjustment. It can be used for approaches using the original measurements, the coordinates of the measured points, or only the offsets between surfaces.

## 1 INTRODUCTION

Airborne laser scanning is being applied for almost two decades now, and has proven to be a suitable technique for terrain determination and object reconstruction (e.g., houses). Data is collected strip wise and direct georeferencing with GPS and IMUs is applied to transform the range and angle measurement from the local sensor coordinate system to the global (WGS84) system, and then usually to some national datum. In the processing of the navigation data, i.e., the computation of the sensor's flight path and orientation in time, the observation (GPS, IMU) errors are minimized. Naturally, this process does not consider any effects on the ground. Likewise "on-the-fly" calibration of the entire system consisting of the ranging unit, the beam deflection device (scanner), and GPS and IMU, componentwise but also their relative orientation, is not performed by standard.

As a consequence from both, the flight path determination which is based only on the GPS and IMU measurements and missing or poor calibration before or after the mission, the laser points computed will not lie on the ground, but are offset in planimetry and height. Practice has shown that offsets of several decimetres can be encountered, which aggravates the reconstruction of the terrain surface or other objects. Effects of the calibration (e.g. a wrong offset between GPS antenna phase center and reference point of ranging) have an effect on the entire block of laser scanner strips, whereas the errors of GPS and IMU vary with time, and therefore also the effects on the ground offsets are different from location to location. These errors on the ground can be categorized into two groups: i) the entire absolute orientation of the block of measurements is wrong, and ii) the strips do not fit to each other. These errors can be minimized with the procedure of strip adjustment (see literature review in Sec. 2), requiring measurement of these offset values in the overlapping part of the strips and offsets to ground control data.

As laser scanning sample surfaces by points and not edges or distinct landmarks, no homologous points can be found in two overlapping strips. Instead correspondence between surface elements from either strip or between a surface element in one strip and a point in the other strip has to be established. The main contribution of this paper is to show how segmentation of laser scanner data can be used to automatically acquire homologous surface elements and measure their offset. What is more, the method presented can be applied to all mathematical models of strip adjustment. Also a method to determine the accuracy of tie element measurement is described and an example is presented.

In the following section related work on strip adjustment is presented. First the mathematical models used are briefly reviewed, followed by a description of the methods for discrepancy observation applied so far. Section 3 presents the segmentation method used for splitting a laser scanner strip up into suitable surface elements and obtaining the measurements of discrepancy. In Section 4 the method itself and decisions made in Section 3 are reviewed critically. In Section 5 examples demonstrate the feasibility of this approach.

## 2 LITERATURE REVIEW

### 2.1 Mathematical Models for Strip Adjustment

The approaches to laser strip adjustment can be categorized into two groups. Methods from the first group use only the observed discrepancies in the laser scanner data points from two overlapping strips. Correction functions are determined for each strip, and the parameters of these functions are chosen in order to minimize the discrepancies.

$$\mathbf{p}'_{i,j} = \mathbf{p}_{i,j} + \mathbf{c}_j(\mathbf{p_{i,j}})$$

Where $\mathbf{p}_{i,j} = (x_{i,j}, y_{i,j}, z_{i,j})^\top$ is the $i$-th laser point point measured in strip $j$, and $\mathbf{c}_j$ is the correction function for strip $j$. The point corrected after strip adjustment is $\mathbf{p}'_{i,j}$.

In the simplest case the functions $\mathbf{c}_j$ are only shift vectors, $\mathbf{c}_j = (\Delta x_j, \Delta y_j, \Delta z_j)^\top$ and do not depend on the location within the strip. In (Crombaghs et al., 2000) and (Kraus and Pfeifer, 2001) the correction function applies to the height component alone, using a linear function (vertical offset and tilts in and across flight direction), and polynomials, respectively. Other ones allow correcting shorter wavelength deformations, too. A method that is not restricted to vertical correction, but also removes discrepancies in planimetry was developed by (Kilian et al., 1996), where the function $\mathbf{c}$ has parameters for constant offset and time dependent drifts for shift in and rotation around the three coordinate axes, requiring that the time of the measurement is known. (Vosselman and Maas, 2001) describe a similar method, mentioning, that this model does not allow to correct short time effects caused by the limited GPS accuracy.

The second group of methods is based on a model of the sensor system, relating each point to its original observations: $\mathbf{p}_{i,j} = \mathbf{f}(\mathbf{O}(t_i), \mathbf{R}(t_i), r_i, \alpha_i, \mathbf{s})$, where $t_i$ is the measurement time, and $\mathbf{O}(t_i)$ and $\mathbf{R}(t_i)$ are the origin and the attitude of the platform, determined from GPS and IMU measurements. The laser scanner observations are the range $r_i$, and the angle measurement $\alpha_i$. The vector $\mathbf{s}$ describes the system parameters (e.g. offset between the GPS antenna and the origin of the platform). In the adjustment the corrected laser points become

$$\mathbf{p}'_{i,j} = \mathbf{f}(\mathbf{O}(t_i) + \Delta\mathbf{O}, \mathbf{R}(t_i) + \Delta\mathbf{R}, r_i + \Delta r, \alpha_i + \Delta\alpha, \mathbf{s} + \Delta\mathbf{s})$$

The $\Delta$–terms can be simple constants, functions dependent on time, scale factors, or take other forms.

In the approach of (Burman, 2002) the unknowns are a constant offset and a time dependent drift for $\Delta\mathbf{O}$, and $\Delta\mathbf{R}$ (IMU–sensor misalignment and IMU drift). In (Filin, 2003) additionally an IMU offset, a range offset and a scan opening angle error are considered. In (Filin, 2003) also the capability of least squares adjustment of the mathematical model are exploited to study the requirements for recoverability of different errors. It is necessary to have surfaces with different expositions (i.e., not only horizontal surfaces), and surfaces with different aspects. In (Kager, 2004) the mathematical model has time dependent polynomials for $\Delta\mathbf{O}$, $\Delta\mathbf{R}$, and a constant IMU-sensor misalignment. Corrections are also determined for the observed beam deflection angles across and in flight direction and the range.

### 2.2 Measurement of Discrepancies

Observations can either be i) coordinate-values of tie features, ii) the distance of one laser point in the first strip to a surface element in the overlapping strip, iii) the 3D points which are forced to lie in a homologous tie surface, or iv) the raw measurements (angles and range).

In (Kager and Kraus, 2001) schema points (like photogrammetric Gruber points, but many more in strip direction) are predefined for the location of tie features. Suitable tie features are searched in a spiral pattern growing from each schema point. The requirements are that the inclination of an adjusting plane to the point and its neighbours and the standard deviation of the plane adjustment are small. In (Vosselman, 2002a) and (Vosselman, 2002b) linear features are used to measure offsets.

In (Maas, 2001) a method for matching in a TIN structure is explained. Also the pulse reflectance data may be used, not only the 3D location of the point. (Burman, 2002) applies this method to every $n$-th point (e.g., $n$=1000). The TIN is not always a truthful representation of the measured objects (e.g. houses and terrain), but is also influenced by shadowing effects and above ground objects may be represented in the TIN surface wider than they are in reality. This has to be considered especially when applying TIN matching (Maas, 2001). In this method no reduction of noise is performed for the discrepancy observations.

In (Filin and Vosselman, 2004) segmentation is applied to the overlapping part of the laser scanner strips and the 3D points from either strip are forced to lie in the segmented surface elements. The parameters of the surface elements are updated between the iterations of the strip adjustment, but can also be treated as unknowns in the adjustment normal equations.

In (Kager, 2004) the four corner points of a tie surface participate in the adjustment. Only the surface elements have to overlap, but not the corner points observed by the scan angle and range measurement in the different strips. The parameters of the surfaces are determined simultaneously with the system parameters. The surface elements are found automatically by first sorting the points in a matrix like structure, with the columns parallel to the flight path and the rows across it. Then the points are analyzed stripwise in a moving window of rows, looking for planar surfaces.

Finally it has to be mentioned that many manual methods are being used for strip adjustment. At the AGI (Adviesdienst voor Geo-Informatie en ICT of the Dutch Ministry of Public Works, Transport and Watermanagement, formerly known as Survey Department) a thematic map is being used, as a layer on the laser data, to locate suitable tie surfaces. At those locations the laser data is being checked whether the area is flat, horizontal and its size about 1/4 hectares. Next, height differences are calculated automatically. However, the first step (finding suitable locations) is done manually and therefore it is time-consuming. AGI is interested in finding tie surfaces automatically.

## 3 METHODOLOGY

The method proposed for finding tie surfaces follows the idea of segmenting the laser data. However, in a first step the *outlines* and *overlapping areas* of the strips are determined approximately. Then the points from one strip in the overlap areas are *segmented* into planar patches. Then these *segments are judged* according to quality (and other) criteria and may be broken up into smaller tie surface elements. To *measure the discrepancy* the height of the segment (the plane) is compared to a plane formed by the points in the other strip. Finally, the consideration of *control areas* will be explained in this section.

### 3.1 Strip outlines and overlaps

For each strip the outline is determined by computing an adjusting line through the ground projection (2D) of all laser points. The direction of this line is the eigenvector to the bigger eigenvalue of diagonal matrix of moments ($\sum \overline{x}^2, \sum \overline{xy}, \ldots$) reduced to the centre of gravity, which is also a point on this line. The outlines are obtained by parameterizing the 2D points with this line, i.e., determining the position along the line and perpendicular to it. The maxima and minima of these values determine the rectangular strip outline.

To get the overlapping areas the strip outlines are intersected. As no restriction on strip direction or numbering is imposed each strip is tested against each other strip. Then each strip overlap is tested against all strip outlines, excluding those, that form the overlap. This yields triple overlaps. This procedure is continued to get higher-fold overlaps until no intersections can be found anymore. An image of the strip outlines and overlaps is shown in Fig. 1.

### 3.2 Segmentation

The overlapping areas are processed independently. The points in the overlap from one strip are segmented, the points from the other strip(s) are not used in this step. The segmentation method applied is based on the method specified in (Filin, 2002).

In the segmentation only planar surfaces are extracted. For each point a feature vector is computed, containing the points normal vector, which is computed from the neighbouring points. The feature space is quantized and clusters are extracted from feature space, starting with the biggest cluster first. As many (planar) surfaces can have the same orientation one cluster corresponds –

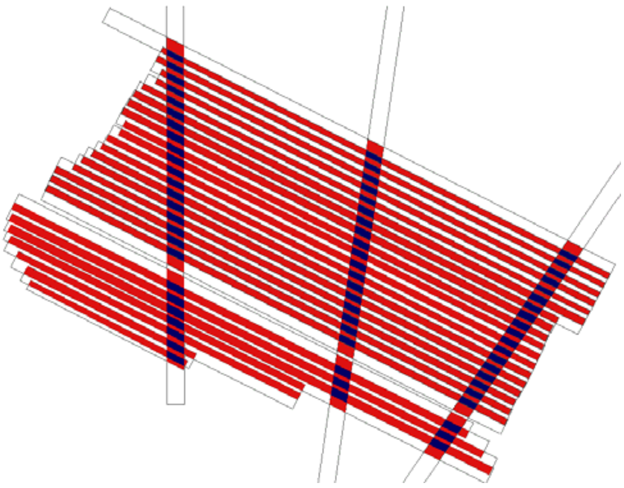

Figure 1: Strip outlines, overlapping areas, and triple overlapping areas.

in general – to multiple surfaces within the overlapping zone. Region growing based on distance is applied to the extracted points in order to separate these surfaces, breaking a cluster up into segments. The choice of the seed within the points not segmented yet has no influence on the result. This method can also be considered as detecting blobs in the clusters. In a validation phased the fitting accuracy of the points from one segment to a plane is tested against a preset accuracy. This allows control over the surfaces extracted, ensuring that these surfaces are actual, physical surfaces and not only points lying on one mathematical surface. Additionally, setting the minimum size of the segment gives additional control over the segmentation process, leading to reliable surfaces.

In the above described algorithm a neighbourhood has to be used i) for normal vector computation, and ii) for the region growing phase. A neighbourhood system that defines points within a certain distance as neighbours is used. This radius is defined in order to reach a certain precision in the normal vector computation. A more comprehensive description of this neighbourhood can be found in (Filin and Pfeifer, 2005).

The result of segmentation applied to a cross overlap of two strips is shown in Fig. 2. A total number of 129000 points are in this overlap, of which 75% are in segments with a minimum size of 30 points. The average segment contains 160 points.

### 3.3 Tie surface definition and selection

After the segmentation of the points in the overlapping zone from one (the first) strip, the points from the other strips in the overlapping zone belonging to the segments have to be selected. Two criteria are applied in the first selection step: 1) the points from the other strip(s) have to be surrounded by segment points from the first strip, and 2) the points from the other strip(s) must be within a maximum vertical distance to the surface element. Both criteria are required to assure that the points from the other strip belong to the same surface element as the points from the first strip. While the need for the first criterion is obvious, the second criterion arises in cases where the ground below vegetation points is provided as one segment, or in the case of layered surfaces, e.g., the points below a bridge. After this external test of the points, an internal validation is performed. A surface (a plane) is fitted to the points of the other strip and robust adjustment is applied to remove points not belonging to the surface element (see Fig. 2, right).

The method described so far can be applied for any mathematical model of strip adjustment. If original measurements or the 3D points are used ((Kager, 2004), (Filin and Vosselman, 2004)) the correspondence from points of different strips to one segment is everything that is required. Otherwise, the tie surfaces are used to compute offsets between the features, either in the direction of the vertical or in the direction of the normal vector. First the barycentre of all the points from one segment, i.e., from both strips, is set as the local origin. Planes are fitted to the point sets of the individual strips, and their offset at the barycentre is determined.

The following two paragraphs describe methods for selecting segments based on quality and distance criteria. They apply specifically to the strip adjustment method applied by AGI. Strip adjustment at AGI is meant to quantify several quality parameters of the laser scanner data provided by flying companies. It has to be mentioned that data providers already performed a kind of transformation to the national datum. At AGI tie surfaces are selected not to improve the data by performing the actual strip adjustment, but to be able to certificate the data (Crombaghs et al., 2002).

In each strip overlap at least 20 segments are selected, resulting in as many offsets per overlap. These offsets are used for two purposes: 1) to determine stochastic errors, which may be caused e.g. by GPS and IMU. Covariance functions are used to separate short and long term errors. Restrictions to the tie surfaces are that the size of the segment should not be too large and that the distance between two surface elements (sample spacing) should be larger than the width of the short term error (Crombaghs et al., 2002), and 2) input in a least squares strip adjustment, together with the offsets between laser data and control areas. In this case only a 1D strip adjustment is calculated, so only flat and horizontal segments are selected.

Depending on the mathematical model of strip adjustment a restriction on the maximum and minimum surface size may be set, e.g., if representative tie points are computed from the segments. This requirements may be specified in terms of number of points or size and shape. By breaking up a big segment into smaller segments the entire tie information can be maintained. The ground plane projections of the points of one segment are used to compute the moments, as for the computation of the strip outline. The eigenvector belonging to the smaller eigenvalue is used as the splitting direction, and the splitting line interpolates the points barycentre. This procedure is applied recursively, until all subsegments fall below the maximum point number, or the length restrictions.

Finally, if only a selection of the points in the overlap direction shall be used, the barycentres of the points are used to compute an adjusting line. Along this line the barycentres are sorted, and a quality criterion (e.g., number of points, fitting accuracy) is used to select the best surface segment. The tie surfaces in the neighbourhood, specified by a length measure, are discarded, and the search for the best surface segment among the remaining one continues.

Other selection criteria for segments include inclination, e.g., for height adjustment, or similarity of the normal vectors from the points from the first and second strip as another measure to avoid faulty correspondences.

### 3.4 Control areas

Control points or control surfaces are required to determine the datum of the entire block of laser strips. If control surfaces are given, i.e., a groups of points on a smooth surface, the determination of the corresponding points in the laser strips is preformed in the same way as for the measurement of tie surfaces. The difference is, that here only validation is performed for the selected laser points inside the control surface.

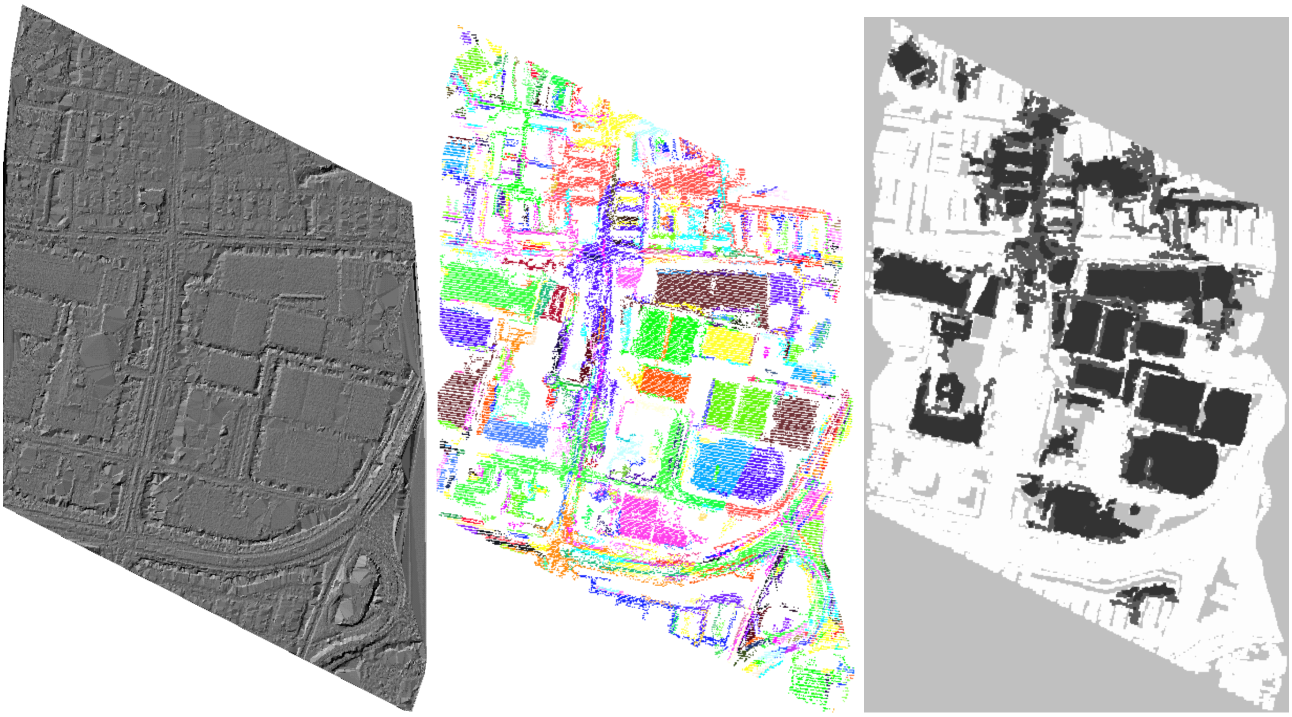

Figure 2: Segmentation and surface element selection of a cross overlapping zone. Left the points from the first strip are shown in a triangulation. In the middle the segmentation result of the first strip is presented. Different segments are shown in different shades. Right the results after the tie surface selection are shown: the white points are the points of the first strip which do not belong to a tie surface, the grey points are those selected for a tie surface, and the black points, overlaying the grey points, are those points of the second strip corresponding to one of the tie surfaces.

## 4 CRITICAL ANALYSIS OF PROPOSED METHOD

The method begins by computing the *outlines* of the strips. In the above we suggest using rectangles, because the have the following advantages: i) they describe a convex polygon around the points, ii) with current flying patterns (no curves) they practically follow the overall shape very well, and iii) they are easy and fast to compute. The fact that they are convex does not only allow to use easier intersection algorithms (note that intersections of convex polygons are also convex), they also assure that the outline of the strip is exactly one polygon. An alternative approach is to compute a tight polygonal outline of the laser strip. A general shape outline requires adequate (and more elaborate) polygon intersection algorithms that are harder to implement.

*Segmentation* is applied to the points of one strip only. Merging the points first and applying segmentation in the next step would suffer from the discrepancies which shall be removed. The segmentation uses the entire available data to search tie surfaces, which is to be preferred to using schema points which can detect discrepancies only near the schema points. Especially if the discrepancies do not vary continuously (e.g., because of change in the visibility of a GPS satellite), these jumps may not be detected.

The segmentation method described above is capable of retrieving multiple surfaces atop each other (e.g., street below and on top of a bridge), and there is not reason to discard one or the other surface beforehand. Even more important, roofs often feature inclinations stronger than those of the terrain, and as it has been shown in (Filin, 2003) surfaces with different slopes are required to resolve errors. Points on the vegetation, on the other hand, do not form a segment because they do not lie on a surface. Only in the step of selecting the points from the other strips, vegetation has to be considered.

Alternative segmentation methods, e.g., based on region growing can be applied, too. Practice has shown that many surfaces can be found in dense laser scanner data, and finding smaller segments with a faster segmentation method is expected not to be harmful for the subsequent strip adjustment. However, a (simple) surface model (e.g., local plane, local low order polynomial) has to build the basis of the segmentation. This is necessary either for feature determination or for formulating the correspondence equations, i.e., formulating that points from different strips belong to the same surface.

The entire overlap may contain a million points. Thus it may be advisable to split the overlap in length direction multiple times to speed up computation. This depends, of course, on the segmentation method applied.

### 4.1 Accuracy of discrepancies

To get an estimation of the accuracy of this tie surface measurement method the following experiment was performed. One strip was input twice into the entire tie surface determination procedure: computation of outlines, segmentation of the first strip, and point collection in the second strip followed by offset measurement in the vertical direction. However, not an exact copy of the strip was used as second strip, but a deformed copy of the original strip. The discrepancies observed in the tie surfaces should then correspond to the deformation applied beforehand.

The deformation was applied to the height component alone and split into four parts. The first part shows no deformation, the second is a linear function rising to 10cm, the third showing a constant height offset of 10cm, and the last a quadratic function, rising from 10cm to 22cm in the area of the strip.

The original data was segmented (Sec. 3.2), and the deformed copy was used to select the points (Sec. 3.3) tieing to the segments. Only flat surfaces (inclination below 3°) were selected, the minimum number of points set to 30, corresponding to $6m^2$, and the segments with more than 300 points were split up into smaller segments. In the strip extends of 800m by 30km almost 4000 tie surfaces were found.

Fig. 3 shows the deformation function of the strip as solid line. The marks show observed height discrepancies. As it can be seen, the height discrepancies follow the deformation model. Points were found along the entire strip, only on the eastern end a water body spanned over the entire swadth width, returning no points during laser measurement.

The difference from the actual deformation and the model deformation was computed for the barycenter of each tie surface. The spread of this discrepancy observations around the true value is $\pm$23mm, the average is 0.4mm. The maximum deviations are -18cm and +21cm. The explanation for the deviations can be found in the selection for the points from the second strip. As the points of the tie surface in the second strip are always within the limits of the points from the first strip, the point sets are not the same. Therefore the parameters of the adjusting planes are not the same. The deviation from the observed and the true deformation depend on both, the number of points in the segmented surface (first surface), and the number of points in the surface generated from point selection (second surface). More specifically, the deviation between observed and true deformation become smaller with i) higher number of points in the second surface, and ii) a ratio of points in the first and second surface closer to one. There is also a dependency on the number of points in the first surface, but this dependence is not as strong. For tie surfaces with more than 135 points in the second surface, the maximum absolute deviation is below 10cm, for more than 200 points the maximum absolute deviation is below 5cm. Not only the maximum error, also the spread becomes smaller accordingly. With decreasing number of points in the first surface, only the maximum error becomes smaller, but not the r.m.s. error. If the ratio of points is larger than 0.8, the maximum absolute deviation is below 5cm, for smaller ratios it reaches 20cm. However, the ratio of points number values computed in this experiment are not realistic, because a ratio of 1 means, in many cases, that exactly the same points from the original and deformed strip were used (disregarding the height deformation), which cannot be the case if two different strips are compared to each other. The conclusion to be drawn is that with larger number of points in a tie surface the observations become more reliable.

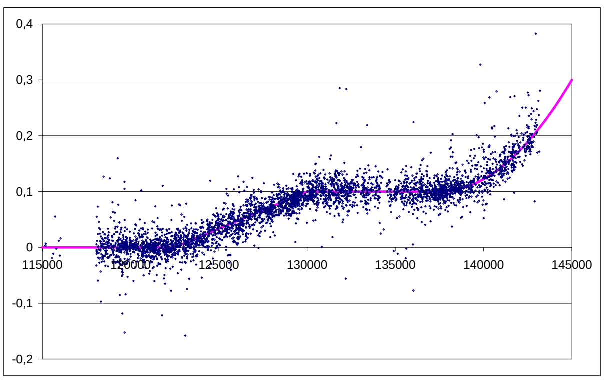


Figure 3: Observed discrepancies (marks) and applied deformation (solid line) between a strip and a deformed copy of itself. The horizontal axis shows the X-coordinate, which is near parallel to the strip axis, and the vertical axis shows the observed discrepancy in metre.

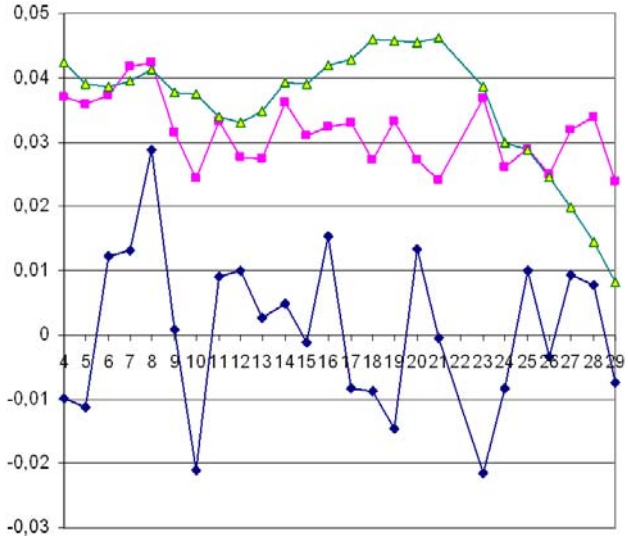


Figure 4: Discrepancies between overlapping length strips in metre, the horizontal axis is the number of the segmented strip. (The strip outlines are shown in Fig. 1.) The diamond shaped marks show the average vertical discrepancy in metres. The square symbols show the standard deviation in metres of the discrepancies in the overlap with respect to the mean discrepancy. The triangle symbols show the number of tie surfaces used in units of 4000 (0.05 corresponds to 200 tieing point measurements).

## 5 EXAMPLE

The project area size is about 70.000 hectares. With a flying height of 1000 metre, speed of $80ms^{-1}$, and strip width of 830 metre, about 50 strips were needed to cover the area. The strips were flown with 20% length overlap, resulting in a 166 metre wide overlap area. The point density is about 0.2 point per $m^2$. The data was acquired for the AGI in autumn 2003. The area covers the water board “Amstel, Gooi and Vecht” which was the first organization updating their part of the national Dutch height model, the AHN. The area is relatively horizontal, which requires a very precise determination of height for enabling hydrological run-off calculations or study influences of setting the ground water level to a certain level. As only low and moderate slopes are found in this area, the influence of planimetric offsets on the reconstructed terrain is very low. In this example 30 strips are taken into account, including three cross strips. The strip outlines and overlaps can be seen in Fig. 1.

As mentioned above, at AGI a strip adjustment method is restricted to the height component alone. A requirement is that the surface segments have between 30 and 300 points in order to avoid too small segments (low accuracy) and too large segments (spanning over too large areas in order to be able to separate short and long term errors in covariance functions as mentioned in 3.3). Another restriction is applied to the maximum slope of a segment, which is in this case 3°. Tie surfaces must have at least a diameter of 3m and the accuracy of the fitted plane must not be worse than 10cm. Tie surfaces have to be at least 100 metre apart in strip direction, because they shall belong to different GPS observations. Measurements of discrepancies are only applied pairwise between strips, therefore no extra use was made of the triple overlaps.

The average shift value between two strips was found to range between -2cm and +3cm. For the length strips these average shifts can be seen in Fig. 4.

The standard deviation of all discrepancies within one strip ranged from $\pm$2cm to $\pm$4cm. With the accuracy measure derived

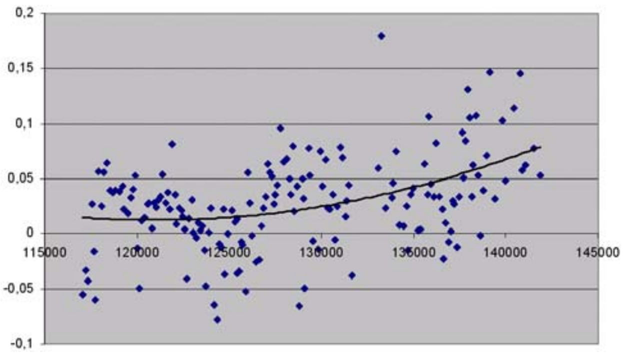


Figure 5: Selected vertical discrepancies between strips 8 and 9 in metre. The horizontal axis shows the x-coordinate, which is near parallel to the strip axis.

above in Sec. 4.1 of ±2cm this indicated that not only a constant offset can be found between tie surfaces, but also some variation within the offsets. The height discrepancies between strips 8 and 9 are shown in Fig. 5. The average value is +3cm with a spread of ±4cm. They clearly follow a trend. In Fig. 5 a second order polynomial is fitted to the offsets, but it can be clearly seen, that there is more systematic variation in the offset values.

Before using the automatic method the discrepancy measurements were performed manually. For a project of this size this requires one man week of work. The quality of a single manual measurements is considered to be higher, because humans make interpretations not based on geometry alone. This is, however, outperformed by the number of automatically generated discrepancy observations. Additionally, the automatic processing speeds up the process of checking the data and requires less operator attendance.

## 6 CONCLUSIONS

We presented a general method for determining discrepancies between overlapping strips. It can provide input for various algorithms of strip adjustment. Discrepancies are not measured between points or points and triangles, but between surfaces.

The method of determining discrepancies between strips proceeds by first determining pairwise overlap between all strips, then triple and higher-fold overlaps are determined. It was shown that rectangles provide suitable outlines for the strips in this process.

Next, the points in the overlap from one strip are segmented. As it has been shown, segmentation offers the possibility to measure discrepancies between overlapping laser strips. The segmentation methods suitable for providing input to strip adjustment algorithms have to use a (simple) surface model for each tie surface, e.g. a plane. The segmentation approach allows to tie surfaces together along the entire overlap of neighbouring strips.

After segmentation the points from one strip from the overlapping strip have to be selected. Depending on the method of strip adjustment used, large tie surfaces may be broken up into smaller ones, or surfaces with larger inclinations may be discarded.

The method was demonstrated on a data set with 30 strips. Height discrepancies in the overlap are not constant by vary along the overlap length direction. The accuracy of a single discrepancy observation is in the order of 2cm.

## REFERENCES

Burman, H., 2002. Laser strip adjustment for data calibration and verification. In *International Archives of Photogrammetry and Remote Sensing, Vol. XXXIV, 3*, pp. 67–72, Graz, Austria.

Crombaghs, M., Brügelmann, R., and de Min, E., 2000. On the adjustment of overlapping strips of laseraltimeter height data. In *International Archives of Photogrammetry and Remote Sensing, Vol. XXXIII, 3A*, pp. 230–237, Amsterdam, Netherlands.

Crombaghs, M., Oude Elerink, S., Brügelmann, R., and de Min, E., 2002. Assessing height precision of laser altimetry DEMs. In *International Archives of Photogrammetry and Remote Sensing, Vol. XXXIV, 3A*, pp. 85–90, Graz, Austria.

Filin, S., 2002. Surface clustering from airborne laser scanning data. In *International Archives of Photogrammetry and Remote Sensing, Vol. XXXII, 3A*, pp. 119–124, Graz, Austria.

Filin, S., 2003. Recovery of systematic biases in laser altimetry data using natural surfaces. *Photogrammetric Engineering & Remote Sensing*, 69(11):1235–1242.

Filin, S. and Pfeifer, N., 2005. Neighborhood systems for airborne laser data. *Photogrammetric Engineering & Remote Sensing*, 71(6):743–755.

Filin, S. and Vosselman, G., 2004. Adjustment of airborne laser altimetry strips. In *International Archives of Photogrammetry and Remote Sensing, Vol. XXXV, B3*, page 5, Istanbul, Turkey.

Kager, H., 2004. Discrepancies between overlapping laser scanning strips - simultaneous fitting of aerial laser scanner strips. In *International Archives of Photogrammetry and Remote Sensing, Vol. XXXV, B/1*, pp. 555–560, Istanbul, Turkey.

Kager, H. and Kraus, K., 2001. Height discrepancies between overlapping laser scanner strips – simultaneous fitting of aerial laser scanner strips. In Grün and Kahmen, editors, *Fifth Conference on Optical 3-D Measurement Techniques*, pp. 103–110, Vienna, Austria.

Kilian, J., Haala, N., and Englich, M., 1996. Capture and evaluation of airborne laser scanner data. In *International Archives of Photogrammetry and Remote Sensing, Vol. XXXI, B3*, pp. 383–388, Vienna, Austria.

Kraus, K. and Pfeifer, N., 2001. Advanced DTM generation from LIDAR data. In *International Archives of Photogrammetry and Remote Sensing, Vol. XXXIV, 3/W4*, pp. 23–30, Annapolis, MD, USA.

Maas, H.-G., 2001. On the use of pulse reflectance data for laserscanner strip adjustment. In *International Archives of Photogrammetry and Remote Sensing, Vol. XXXIV, 3/W4*, Annapolis, MD, USA.

Vosselman, G., 2002a. On the estimation of planimetric offsets in laser altimetry data. In *International archives of Photogrammetry and Remote Sensing, Vol. XXXIV, 3A*, pp. 375–380, Graz, Austria.

Vosselman, G., 2002b. Strip offset estimation using linear features. In *3rd International Workshop on Mapping Geo-Surfical Processes using Laser Altimetry*, Columbus, Ohio, USA.

Vosselman, G. and Maas, H.-G., 2001. Adjustment and filtering of raw laser altimetry data. In *Proceedings of OEEPE Workshop on Airborne Laserscanning and Interferometric SAR for Detailed Digital Terrain Models*, Stockholm, Sweden.