AIRBORNE LASER SCANNING STRIP ADJUSTMENT AND AUTOMATION OF TIE SURFACE MEASUREMENT[1]

Ajustamento de faixa do varredor laser aerotransportado e automação de medidas na superfície de ligação

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ABSTRACT

Airborne laser scanning of the earth surface and other objects on top it yields measurements of unstructured point clouds in a strip wise manner. Often multiple length strips with a small overlap are observed, sometimes augmented by a few cross strips for validation purposes. Due to inaccurate calibration of the entire measurement system and due to the limited accuracy of direct geo-referencing (i.e., the exterior orientation determination) with GPS and IMU, including systematic errors, adjacent strips may have discrepancies in their overlap. For removing these discrepancies strip adjustment algorithms require quantification on these offsets at various locations within the overlapping zones. Different methods of strip adjustment are reviewed, followed by the presentation of a general method for determining the discrepancies automatically. This method – the core of the paper – is based on segmenting the point cloud in the overlap. In the examples, mean offsets between neighboring strips in the order of a few centimeters are reconstructed. The offsets also show substantial variation along the strip. The method developed for discrepancy determination can be applied to height or full 3D strip adjustment and for approaches using the original measurements, the coordinates of the measured points, or only the offsets between surfaces. An example of strip adjustment using discrepancy observations with the method presented and a discussion of the results conclude this paper.

[1] This article is partly based on Pfeifer, Filin, Oude Elberink: Automatic tie elements detection for laser scanner strip adjustment. Submitted to ISPRS Workshop Laserscanning 2005, Enschede, The Netherlands.

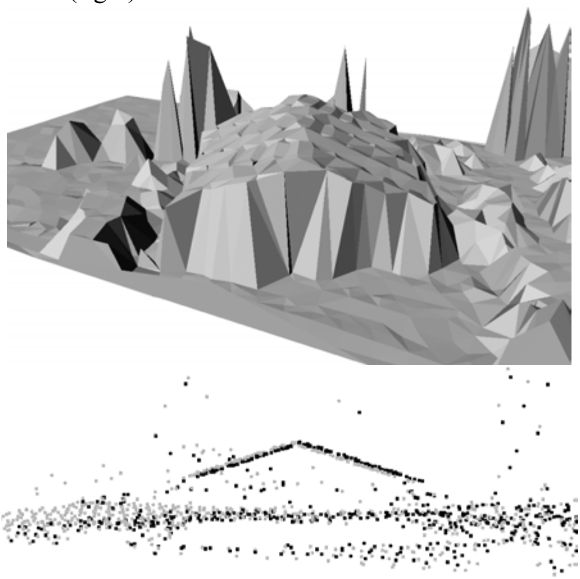
1. INTRODUCTION

Airborne laser scanning is a method for the efficient measurement of points on the earth surface and on other surface on top of it, e.g. tree canopy surface and roofs. It is being applied routinely now and has proven to be a suitable technique for terrain determination and object reconstruction, e.g. for buildings. Data is collected strip wise from the airborne platform and direct geo-referencing 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. "On-the-fly" calibration of the multi sensor system – consisting of the ranging unit (laser range finder, LRF), the beam deflection device (scanner), and GPS and IMU – is not performed routinely for a laser scanning mission. The calibration includes component wise calibration and the relative orientation between the individual components.

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 decimeters 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: firstly, the entire absolute orientation of the block of measurements is wrong, and secondly, the strips do not fit to each other.

An example of these errors is shown in Fig. 1. In the left image the point clouds from two overlapping strips were joint and triangulated. The scene shows a house and vegetation. In the right image the raw points are shown, with points from the first strip in black and points from the second strip in grey. The horizontal offset between the roof points from the different strips is apparent.

Figure 1: Triangulation of the laser scanner point cloud in an overlap between two strips (left), and raw points from the different strips shown in different gray tones (right).



The effects of missing calibration or systematic errors in direct geo-referencing can be minimized with the procedure of strip adjustment (see literature review in Sec. 2). This requires measurement of the 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 small surface patches from either strip or between a patch 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, also called discrepancy. What is more, the method presented can be applied for all mathematical models of strip adjustment.

In the following section an overview on 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 patches and obtaining the measurements of discrepancy. In Section 3.5 the method is discussed critically. In Section 4 an example with 30 strips is used to demonstrate the feasibility of this approach. First the discrepancy observations are performed, and then strip adjustment for the height component alone is applied. In the last Sections conclusions are drawn.

2. STRIP ADJUSTMENT REVIEW

2.1 Mathematical models of strip adjustment

The approaches to laser strip adjustment can be categorized into two groups. The methods from the first group use only the observed discrepancies in the laser scanner data points from two overlapping strips. Therefore they are also called data driven. 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 $\mathbf{p}_{i,j} = (x_{i,j}, y_{i,j}, z_{i,j})$ 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, $\mathbf{c}_j = (\Delta x_j, \Delta y_j, \Delta z_j)$ 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. The approach of [Kraus and Pfeifer, 2001] allows 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 **c** has parameters for constant offset and time dependent drifts for shift in and rotation around the 3 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. Knowledge on the measurement time is not required but replaced by parameterization along the strip axes.

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 α_i. The vector **s** describes the system parameters (e.g. offset between the GPS antenna and the origin of the platform). Such models are used in the first place in the system vendor's software to convert from the original laser scanner measurements to the points observed by the scanner. 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 Δ–terms can be simple constants, functions dependent on time, scale factors, or take other forms.

In the approach of [Burman, 2002] the unknowns (the "Δ-terms") are a constant offset and a time dependent drift for ΔO, and ΔR (IMU–sensor misalignment and IMU drift). In [Filin, 2003] additionally an IMU offset, a range offset and a scan angle error are considered. In [Filin, 2003] also the capability of least squares adjustment of the mathematical model is 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 ΔO, ΔR, and a constant IMU-sensor misalignment. Corrections are also determined for the observed beam deflection angles across and in flight direction and the range.

These models can be used in two scenarios. Firstly they can be used to calibrate the entire system. In this case the unknowns, e.g. the offset between GPS antenna phase centre and the reference point of ranging, i.e. a constant ΔO, are usually determined for the entire block. Secondly they can be used on-the-job to determine small offsets between calibration values and actual values or to handle drift effects, e.g. the IMU drift for each strip, i.e. a linear, time-dependent ΔRj(t).

2.2 Measurement of Discrepancies

The mathematical models described so far did not include an explanation of the observations used for strip adjustment, but only the correction of the points. Observations can either be i) (coordinate-)values of tie features, ii) the distance of one laser point in the first strip to a patch in the overlapping strip, iii) the 3D points which are forced to lie in a homologous tie patch, 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 search 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] methods for automatic measurement of offsets with linear features are described. A line in planimetry can be used to measure an offset in one direction, a line in 3D space, e.g. the ridge of a house, can be used to measure an offset in the vertical and one horizontal direction.

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 patches. The parameters of the patches 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 raw angle and range measurement are used as observations in the four corner points of a tie patch. Only the patches have to coincide, but not the corner points observed in the different strips. The parameters of the patches are determined simultaneously with the system parameters. The patches 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 strip wise in a moving window of rows, looking for planar patches.

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) a thematic map is being used, as a layer on the laser data, to locate suitable tie patches. 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.

3. AUTOMATIC DETECTION OF TIE AREAS AND DISCREPANCY MEASUREMENT

The method proposed for finding tie surfaces follows the idea of segmenting the laser data. In a first step the overlapping areas are determined approximately. Then the points in the overlap areas are segmented. These segments are then judged according to quality (and other) criteria and may be broken up into smaller tie surfaces.

3.1 Strip outlines and overlaps

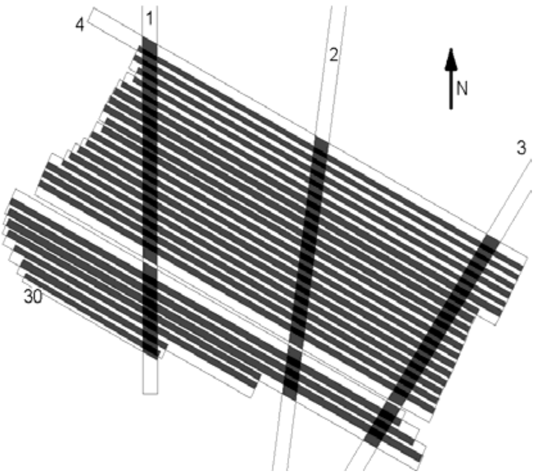
For each strip the outline is determined by first computing an adjusting line through the ground projection (2D) of all laser points. This line resembles the strip axis. Its direction **v**1 is the eigenvector to the bigger eigenvalue λ1 of the diagonal matrix of moments reduced to the center of gravity:

$$\begin{pmatrix} \sum \bar{x}_i^2 & \sum \bar{x}_i \bar{y}_i \\ \sum \bar{x}_i \bar{y}_i & \sum \bar{y}_i^2 \end{pmatrix} = (\mathbf{v}_1, \mathbf{v}_2)^{\mathrm{T}} \operatorname{diag}(\lambda_1, \lambda_2)(\mathbf{v}_1, \mathbf{v}_2)$$

with λ1 > λ2. The xi, yi are the planimetric coordinates of the points of one strip and the line above denotes the reduction to the centre of gravity (Σxi/n, Σyi/n). This point is also a point on the adjusting 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. 2.

Figure 2: Strip outlines, overlapping areas, and triple overlapping areas. Strip numbers and the geographic orientation, used throughout this paper are shown, too.



3.2 Segmentation

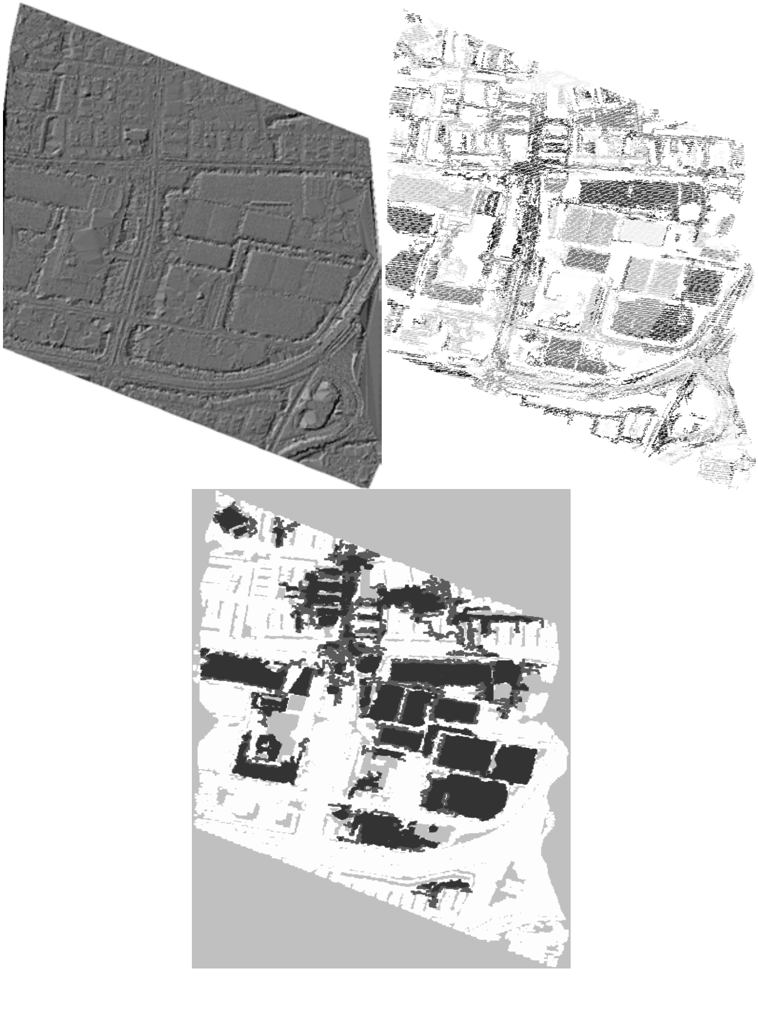
The overlapping areas are processed independently. The points in the overlap from one strip are segmented, the points from the other strip(s) are not used in this step. The segmentation method applied is based on the method specified in [Filin, 2002].

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 neighboring 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 – in general – to multiple surfaces within the overlapping zone. Region growing is applied to the extracted points in order to separate these surfaces, breaking a cluster up into segments. In a validation phase 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 surfaces and not only points lying on one mathematical surface. Additionally, setting the minimum size of the segment gives control over the segmentation process, leading to reliable surfaces.

In the above described algorithm a neighborhood has to be used for normal vector computation, and for the region growing phase. A neighborhood system that defines points within a certain distance as neighbors is used. This radius is defined in order to reach a certain precision in the normal vector computation. A comprehensive description of this neighborhood can be found in [Filin and Pfeifer, 2005]. Very roughly speaking, this neighborhood system leads to about 12-15 neighbors per point, which are – for smooth surfaces – the 12-15 nearest points.

The result of segmentation applied to a cross overlap of two strips is shown in Fig. 3. 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.

Figure 3: Segmentation and patch 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.



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 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. 3, 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. For this first the barycenter 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 barycenter is determined.

The following 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]. Therefore, the procedure of strip adjustment at AGI will be described in more detail now.

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.

Not only in the context of strip adjustment mentioned above, but generally 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 requirement 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 barycenter. This procedure is applied recursively, until all sub-segments fall below the maximum point number, or the length restrictions.

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 performed in the same way as for the measurement of tie surfaces. The segmentation step does not have to be performed because the terrestrial points in one control area form one segment already. Only the validation step is performed for the selected laser points inside the control surface.

3.5 Critical discussion

The method begins by computing the outlines of the strips. In the above we suggest using rectangles, because the have the following advantages: 1) they describe one convex polygon around the points, 2) with current flying patterns (no curves) they practically follow the overall shape very well, and 3) 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. This can be done e.g. by triangulating the laser data and omitting those edges that are longer than a certain threshold. A general shape outline, which may consist of multiple polygons for one strip, requires adequate (and more elaborate) polygon intersection algorithms and more involved processing.

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. This means that vegetation removal algorithms do not have to be applied first. Especially as houses – typically with roof surfaces with different gradient and aspect – might also be removed with these algorithms their application is more harmful than helpful for strip adjustment.

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. EXAMPLE

The project area of the example has a size of about 70.000 hectares. With a flying height of 1000 metre, speed of $80ms^{-1}$, and strip width of 830 meter, about 50 strips were needed to cover the area. The strips were flown with 20% length overlap, resulting in a 166 meter 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 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. 2.

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 meter apart in strip direction, because they shall belong to different GPS observations. GPS observations were performed with a frequency of 1Hz. Measurements of discrepancies are only applied pair wise 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 ±2cm to ±4cm. Assuming a discrepancy measurement accuracy of ±2cm (the minimum r.m.s. discrepancy between two strips in this data set) 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 first order polynomial (a line) is fitted to the offsets, but it can be clearly seen, that there is more systematic variation in the offset values.

The quality of a single manual measurement 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.

Figure 4: Discrepancies between overlapping length strips in meter, the horizontal axis is the number of the segmented strip. (The strip outlines are shown in Fig. 2.) The diamond shaped marks show the average vertical discrepancy in meters. The square symbols show the standard deviation in meters 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 tying point measurements).

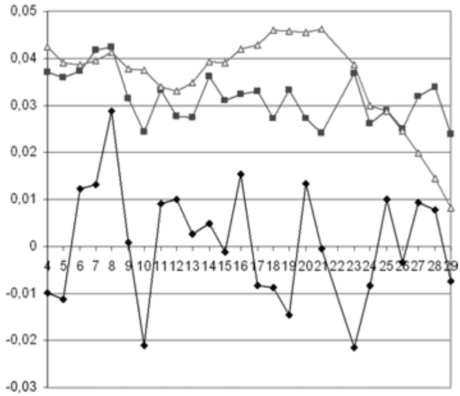
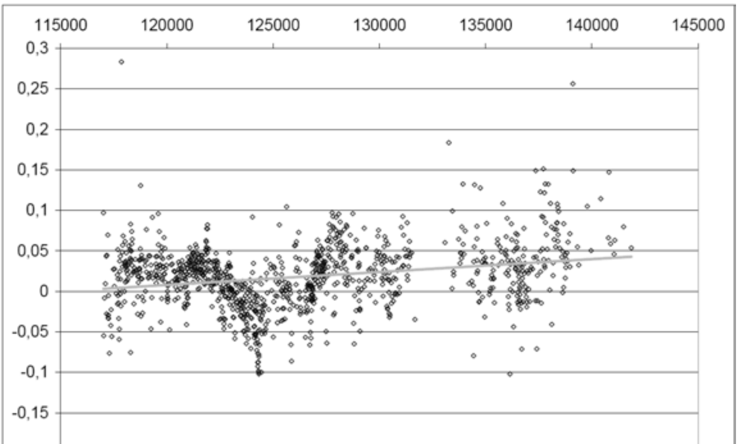


Figure 5: Vertical discrepancies between strips 8 and 9 in meter. The horizontal axis shows the x-coordinate, which is near parallel to the strip axis.



All together 31862 discrepancy observations were found in the overlaps. All these observations were used in a strip adjustment. Additionally, four control areas were measured manually in the field. Because two control areas are found in the overlap of two strips, this leads to six observations for defining the datum of the entire block. The mathematical model of strip adjustment applied is the computation of correction functions for the height component only. To avoid oscillations of the correction functions only a linear polynomial is determined for correction per strip. This is important especially as there is i) only little control information (four control fields), and ii) the cross strips do not cross at the outer ends of the length strips, but especially in the southern part in the middle of the strips (see Fig. 2). No use was made of triple overlaps, only pair wise strip discrepancy observation served as input for the adjustment.

For the adjustment all observations were used, because the area is generally very flat and no disturbing influence of gently sloping tie areas was expected. Also no restriction was applied to the height offset. This has the effect of allowing possibly grossly wrong height offsets to be included, but assuming that their number is small, the effect on the adjustment result is considered negligible. No weighting according to the number of points in the tie area or the accuracy of the plane fit was performed. For the 30 strips 60 unknowns were determined – two parameters of a linear for each strip – by the adjustment of 31686 observations. The a posteriori σ_0 of the adjustment is ±3.1cm, whereas the r.m.s. offset between strips, i.e. the observations, was ±3.5cm. The correction polynomials are plotted in Fig. 6 and a mathematical description is given in Table 1. In the following an analysis of the strip adjustment results is given.

Figure 6: Height correction functions plotted in 3D along the strip axes. Corrections range from -13cm to +11cm, corresponding to black and light gray, respectively, in the image. The extend of the axis parallel box is 40km in east-west and in north-south direction and 24cm in height. The spheres indicate the position of control areas.

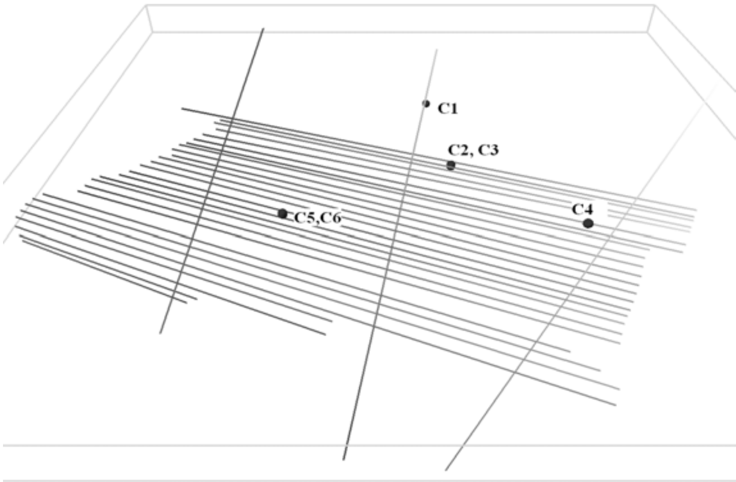


Table 1: Parameters of the linear height correction polynoms. sID is the strip number, where 1, 2, and 3 are the cross strips and the length strips are numbered sequentially starting from 4 as the most northern strip. p-begin and p-end denote the strip begin and end point, and h-begin and h-end the height of the polynomial at begin and end point.

sID	p-begin		p-end		h-begin	h-end
1	118254	496058	118775	460702	-99	-73
2	126558	454844	131860	488245	-118	49
3	130033	454111	149720	482245	-62	107
4	114677	482135	143207	468143	-130	41
5	117651	479962	142934	467645	-98	35
6	117377	479454	142650	467105	-89	54
7	117620	478706	142372	466584	-95	52
8	116849	478420	142112	466099	-120	63
9	116362	477993	141808	465535	-130	31
10	116035	477494	141541	465063	-129	22
11	115724	477018	140045	465150	-111	31
12	115411	476499	139722	464683	-113	20
13	115557	475822	139506	464155	-116	11
14	114869	475527	139280	463601	-108	0
15	114552	475048	139027	463088	-112	-8
16	114019	474644	138778	462544	-110	-8
17	113457	474291	138519	462038	-134	-10
18	112972	473906	138224	461524	-132	-9
19	111941	473745	137934	461037	-136	5
20	111686	473243	137650	460533	-118	12
21	111447	472705	137426	459977	-128	8
22	111231	472192	137201	459448	-131	10
23	109560	471667	135249	459227	-114	-17
24	109267	471091	136133	458160	-105	-6
25	109150	470495	136584	457213	-98	0
26	109114	469946	136394	456688	-101	-32
27	109139	469324	125823	461389	-99	-69
28	109525	468412	125565	460874	-91	-99
29	110054	467646	119724	463123	-89	-104
30	110401	467170	119334	462892	-82	-106

From the four control areas two are situated in the overlap of strips. Therefore six observation equations serve to define the datum (strip 2: C1, strip 4: C2, strip 5: C3, strip 10: C4, strip 18: C5, strip 19: C6). The discrepancies before adjustment ranged from -69mm to +42mm. The r.m.s. discrepancy is ±55mm. After adjustment these values reduces to -43mm to +32mm for the range, and ±30mm for the r.m.s.

residual, respectively. The datum of the block could therefore be improved (reducing the discrepancies roughly to 50%). However, it also shows that there is still a mismatch between the inner geometry of the block of strips and the control areas. Possible explanations are measurement errors in the terrestrial field measurement or calibration errors of the laser system which cannot be detected with the model of strip adjustment applied.

The general datum of the entire block is changed by – more or less – a tilted plane, rising from north-west to south-east. As it can be seen in Fig. 6 the four most southern strips (27,28,29,30) cross only one cross strip and values of the correction polynomials are not controlled at their western end.

The difference in the correction polynomials for strips 8 and 9 is that correction 8 is 1cm higher in the western begin point and 3cm higher in the eastern end point. This corresponds very well to the trend line fitted to the observations between strip 8 and 9 in Fig. 5. Naturally, not all the systematic behavior visible in Fig. 5 is compensated with this model of strip adjustment.

As noted before, the improvement in the strip offsets reduced from ±3.5cm to ±3.1cm. This indicates that most deformation could not be modeled with a linear correction polynomial. Because higher correction polynomials tend to oscillate, an improvement can only be expected from changing the mathematical model of strip adjustment to a sensor model driven approach.

5. CONCLUSIONS

A general method for determining discrepancies between overlapping strips was presented. 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 pair wise 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 tying surfaces together along the entire overlap of neighboring strips.

After segmentation of the points from one strip, the points 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. A simple strip adjustment method was applied in order to homogenize the height of the entire block of laser scanner points. Discrepancies could be reduced, but the simple model was not capable of eliminating all systematic effects. For higher accuracy demands a sensor model driven approach to strip adjustment appears to be necessary.

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