

# INVESTIGATING ADJUSTMENT OF AIRBORNE LASER SCANNING STRIPS WITHOUT USAGE OF GNSS/IMU TRAJECTORY DATA

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## ABSTRACT:

Airborne laser scanning (ALS) requires GNSS (Global Navigation Satellite System; e.g. GPS) and an IMU (Inertial Measurement Unit) for determining the dynamically changing orientation of the scanning system. Because of small but existing instabilities of the involved parts - especially the mounting calibration - a strip adjustment is necessary in most cases. In order to realize this adjustment in a rigorous way the GNSS/IMU-trajectory data is required. In some projects this data is not available to the user (any more). Derived from the rigorous model, this article presents a model for strip adjustment without GNSS/IMU-trajectory data using five parameters per strip: one 3D shift, one roll angle, and one affine yaw parameter. In an example with real data consisting of 61 strips this model was successfully applied leading to an obvious improvement of the relative accuracy from (59.3/23.4/4.5) [cm] to (7.1/7.2/2.2) (defined as RMS values in (X/Y/Z) of the differences of corresponding points derived by least squares matching in the overlapping strips). This example also clearly demonstrates the importance of the affine yaw parameter.

## 1 INTRODUCTION

Over the last ten years airborne laser scanning (ALS) has established itself as the prime data acquisition method for digital canopy and digital terrain models (DTM). ALS uses a multi sensor system and is based on direct georeferencing (Skaloud, 2007); i.e. position and attitude of the scanning system is determined by GNSS (Global Navigation Satellite System) and an IMU (Inertial Measurement Unit). Additionally the correct georeferencing of the original laser scanning measurements requires the internal laser parameters (e.g. zero point and scale of the range and angle measurements) and the parameters of the mounting calibration. This calibration is made up of a rotational part (which describes the rotation between the IMU system and the laser system) and a translational part (which is the vector from the laser centre to the GNSS antenna centre).

Direct georeferencing has the problem, that these mentioned parameters are affected by a certain instability over time (especially the rotation between IMU and laser system). Consequently the values of these parameters during a particular flight will differ from the last known values (e.g. determined during a calibration). These parameters can not be corrected during the GNSS/IMU processing, because there the measurements of the laser scanner do not take part. Even the synchronisation between the GNSS/IMU data and the laser measurements can be wrong. For these reasons the direct georeferencing will use wrong transformation parameters, which will result in wrong 3D coordinates of the measured surface points. In the derived DTM this may lead to e.g. sudden jumps along the strip borders.

For improving the accuracy of the points a strip adjustment, similar to bundle block adjustment, needs to be done usually. During this adjustment the mentioned internal laser parameters, the mounting calibration and the time synchronisation are determined in an optimal way. The GNSS/IMU trajectory data is mandatory for this adjustment. For some projects (e.g. historic ones) only the directly georeferenced point cloud for each strip is available - but no GNSS/IMU trajectory. If the originally delivered points do not pass the quality control, then a strip adjustment without GNSS/IMU trajectory data must be considered.

This paper presents such a strip adjustment without GNSS/IMU

trajectory data. Section 2 derives the respective mathematical model from the rigorous model using effect figures. Section 3 presents first results obtained with this model for a project with 61 strips. A summary with outlook concludes the paper in section 4.

## 2 A MATHEMATICAL MODEL FOR ALS STRIP ADJUSTMENT WITHOUT GNSS/IMU TRAJECTORY DATA

If the GNSS/IMU trajectory is given, then a rigorous strip adjustment can be computed; e.g. (Kager, 2004), (Friess, 2006), (Skaloud and Lichti, 2006), (Burman, 2000), (Filin, 2001), (Kilian et al., 1996). Depending on the used mathematical model, this rigorous strip adjustment determines corrections for the internal laser parameters and the mounting calibration, and also additional parameters (e.g. for the time synchronisation). Afterwards the original surface points  $\mathbf{X}$  will be transformed a second time by these corrected parameters resulting in corrected surface points  $\mathbf{X} + \Delta\mathbf{X}$ . The basis for the adjustment is the transformation equation, which describes the transformation from the original laser measurements to the 3D coordinates of the observed surface points by taking into account the GNSS/IMU trajectory data. Following (Skaloud and Lichti, 2006) this transformation can be written as:

$$\mathbf{X} = \mathbf{X}_{GNSS} + \mathbf{R}_{IMU} \cdot \left( \mathbf{m} - \mathbf{R}_M \cdot \begin{pmatrix} 0 \\ \rho \cdot \sin \theta \\ \rho \cdot \cos \theta \end{pmatrix} \right) \quad (1)$$

$\mathbf{X}$  is the surface point in the reference system. The antenna centre  $\mathbf{X}_{GNSS}$  and the rotation  $\mathbf{R}_{IMU}$  of the IMU determine the position and rotation of the airplane in the reference system. The system of the laser scanner is slightly rotated by  $\mathbf{R}_M$  with respect to the IMU system and shifted by  $\mathbf{m}$  with respect to the antenna centre.  $\mathbf{R}_M$  and  $\mathbf{m}$  make up the mounting calibration. The laser scanner measures the distance  $\rho$  and the deflection angle  $\theta$ .

After the strip adjustment the corrections  $\Delta\mathbf{X}$  of the originally measured points are determined via (1) as function of the 3D coordinates  $\mathbf{X}$ , the measurement time  $t$ , the GNSS/IMU trajectory data, the corrected internal laser parameters  $\Delta i$  (subsuming po-

tential additional parameters like a time correction), and the corrected mounting parameters ( $\Delta R_M \cdot R_M, m + \Delta m$ ):  $\Delta X =$

$$\Delta X(X, t, X_{GNSS}(t), R_{IMU}(t), \Delta R_M \cdot R_M, m + \Delta m, \Delta i) \quad (2)$$

If the original points are to be corrected without GNSS/IMU trajectory data, then a different correction function is needed, which consequently determines different corrections  $\Delta X$  for the original points. These corrections are functions of the original 3D coordinates and new correction parameters  $a_i$ :  $\overline{\Delta X} = \Delta X(X, a_i)$ . Because the dynamics, which are recorded in the GNSS/IMU trajectory data, are not considered, these corrections  $\overline{\Delta X}$  can only be an approximation to the corrections  $\Delta X$  which would have resulted from (2). Thus the question arises, which correction function should be taken.

Whereas for strip adjustment with GNSS/IMU trajectory data many publications exist (see above), the number of publications for strip adjustment without GNSS/IMU trajectory data is fairly limited. Simple approaches only adjust the heights (e.g. (Crombaghs et al., 2000), (Kager and Kraus, 2001)). Because especially the errors of the rotational component of the mounting calibration produce large horizontal errors, these 1D approaches are defeated by 3D approaches. (Filin and Vosselman, 2004) use a 3D shift per strip. (Fritsch and Kilian, 1994) and (Csanyi and Toth, 2007) apply a 3D similarity transformation for each strip. (Vosselman and Maas, 2001) use 9 parameters per strip: a 3D shift, a spatial rotation (3 parameters) and a differential rotation change (3 parameters), whose effect grows linearly with the coordinate in strip direction. This approach thus contains two bi-linear terms and one quadratic term.

Functions of higher order are attached with the potential danger of swing off in uncontrolled areas. Further uncontrolled effects may occur in case of a large number of parameters. Therefore, in general simple functions with only a few parameters are preferred. This is also illustrated by the cited approaches. The most simple functions are linear in their parameters and the coordinates of the points. Experience shows that the errors of the internal laser parameters and of the mounting calibration are very small. Even via the long lever arm of the flying height they produce errors in  $X$ , which usually require only corrections  $\Delta X$  of a few decimetres. Therefore, in this work we pursue a linear correction function. In many projects where we computed strip adjustments (with given GNSS/IMU trajectory) correcting the rotation component  $R_M$  of the mounting calibration turned out to be very effective. Consequently we will aim at a linear formulation for the effect of  $\Delta R_M$  on the surface points. We assume that the flight was done smooth in a straight line with constant height above ground and the terrain is horizontal.

Fig. 1 shows the effects of a wrong rotational component of the mounting calibration on the scanning plane of the laser system. A local x-y-z coordinate system is defined: the x-axis points in flight direction, the z-axis points vertically upwards and the y-axis completes the system to be right-handed. It is useful to represent the rotation parameters as roll, pitch and yaw angles. The roll angle rotates around the x-axis, the pitch angle around the y-axis, and the yaw angle around the z-axis.

Fig. 1 shows that a small error of the pitch component of the mounting calibration in a first order approximation causes a small shift in flight direction. A small error of the yaw component in the first approximation also causes a shift in flight direction - however, it is not constant but increases with the y-coordinate of the surface points. Therefore in the local x-y-z system the effects of

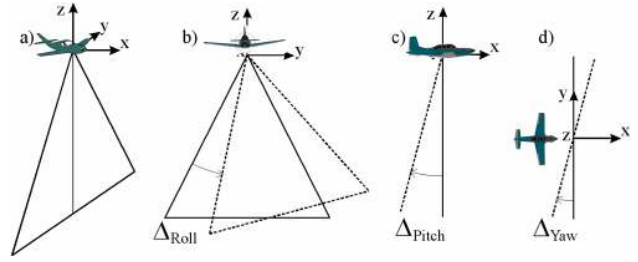


Figure 1: The effect of a wrong rotational component of the mounting calibration on the scanning plane. a) definition of the local x-y-z system with x-axis in flight direction, b) - d) effects of the roll, pitch and yaw component.

the rotation components can be formulated as follows:  $x + \overline{\Delta x} =$

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos a_{roll} & -\sin a_{roll} \\ 0 & \sin a_{roll} & \cos a_{roll} \end{bmatrix} \cdot \begin{bmatrix} 1 & a_{yaw} & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot x + \begin{pmatrix} a_{pitch} \\ 0 \\ 0 \end{pmatrix}$$

$$x + \overline{\Delta x} = R_{Roll} \cdot A \cdot x + a' \quad (3)$$

For applying this correction function on the points  $X$ , which are given in the X-Y-Z reference system, these points must be first transformed to the local x-y-z system. Assuming a flight along a straight line this transformation can be formulated as:

$$x = R_{Z,\alpha} \cdot (X - S) - (0, 0, H)^\top \quad (4)$$

Here  $R_{Z,\alpha}$  represents a rotation around the reference Z-axis by the angle  $\alpha$ , which is the approximate strip direction.  $S$  is the centre of gravity of the surface points in the strip considered.  $H$  is the absolute flying height of the strip, which eventually will turn out to be of no concern. Inserting (4) in (3) yields:

$$x + \overline{\Delta x} = R_{Roll} \cdot A \cdot \left( R_{Z,\alpha} \cdot (X - S) - \begin{pmatrix} 0 \\ 0 \\ H \end{pmatrix} \right) + a'$$

After applying the inverse of (4) on that equation and summation of all vectors to a new vector  $a$  (except for  $S$  for numerical reasons), we get the following correction function:

$$X + \overline{\Delta X} = R_{Z,\alpha}^\top \cdot R_{Roll} \cdot A \cdot R_{Z,\alpha} \cdot (X - S) + S + a \quad (5)$$

This is the basic equation of the ALS strip adjustment without GNSS/IMU trajectory data in this article. It is useful to define the vector  $a = (a_x, a_y, a_z)$  with three unknown elements. This way not only the effect of a pitch error is compensated but also possible other shift errors; e.g. because of a small datum error in the GNSS measurements in each strip. In case of a smooth flight this way also the translational part of the mounting calibration (the so-called lever arm) can be compensated.

Together with the roll angle and the affine yaw parameter this model in total uses 5 unknown parameters per strip. These 5 correction parameters will be estimated in an adjustment so that the discrepancies at corresponding tie objects in overlapping strips and the discrepancies to control objects will be minimised. This correction model reminds of the photogrammetric block adjustment with independent models. There three unknown rotation angles are estimated, here only one angle and one affine parameter are used.

*Remark:* The roll effect in (3) could equally well be modeled by another affine (skew symmetric) parameter in  $A$  instead of an

variant	parameters	Residuals [cm]			Differences [cm]		
		RMS(X)	RMS(Y)	RMS(Z)	RMS(X)	RMS(Y)	RMS(Z)
A	none (orig. georef.)	29.5	11.6	2.2	59.3	23.4	4.5
B	$a_X, a_Y, a_Z$	3.5	3.9	1.7	7.0	7.7	3.1
C	$a_X, a_Y, a_Z, a_{roll}$	3.5	3.6	1.1	7.1	7.2	2.2
D	$a_X, a_Y, a_Z, a_{roll}, (a_{yaw,block})$	3.6	3.6	1.2	7.1	7.2	2.2

Table 1: RMS values of the residuals of the LSM derived tie points at the end of the strip adjustment of different variants (1625 residuals per coordinate).  $a_{yaw,block}$  was averaged from the  $a_X$  results of variant C and used as constant for all strips in variant D. Additionally RMS values of the differences between the LSM derived tie points after the respective adjustment variants are listed (811 differences per coordinate). The residuals refer to the adjusted point, therefore they are approximately half of the differences. The residuals can be computed for each observed point. The differences refer to pairs of observed points. This explains why the number of residuals is practically twice the number of differences.

angle and trigonometric functions.

If the flight direction is east-west, then the model (5) becomes quite simple:

$$\mathbf{X} + \overline{\Delta\mathbf{X}} = \mathbf{R}_{Roll} \cdot \mathbf{A} \cdot (\mathbf{X} - \mathbf{S}) + \mathbf{S} + \mathbf{a} \quad (6)$$

### 3 EXPERIMENTAL RESULTS

In the course of a project, where ALS data was given along the river Main, Germany, terrain edges should be extracted; see (Briese et al., 2009). The ALS data was delivered strip by strip. During the quality control of this delivered data large and systematic residual errors in the overlap of neighbouring strips were detected; see tab. 1, variant A. For this reason it was necessary to improve the georeferencing of the data by means of strip adjustment. Because the GNSS/IMU trajectory data was not available, we had to compute the adjustment without it.

#### 3.1 Setup

The 61 strips (no cross strips) cover an area of ca. 10km (east-west) by 17km (north-south). They overlap by ca. 50% and were flown in east-west direction. Therefore, the simpler model (6) could be applied.

For the strip adjustment corresponding objects in the overlap of the strips are required. Because of positive experience with least squares matching (LSM) for the determination of residual errors between overlapping strips (Ressl et al., 2008) points derived by LSM were used as corresponding objects. For this a DSM was interpolated for each strip with grid width 1m. Afterwards spots suitable for LSM were located manually. Such spots have as many different surface normals as possible; e.g. groups of buildings. Then the actual measurement of the corresponding points was done by LSM using quadratic windows of size 101 pixels. For removing the disturbing effects of vegetation and occlusions (e.g. (Maas, 2000)), LSM only used *smooth* surface pixels. This was achieved using a roughness mask (see (Ressl et al., 2008)). The strip adjustment later estimated the accuracy of these LSM measurements to be ca. 5cm in X and Y and ca. 1.5cm in Z. About 10 to 50 corresponding points were measured per strip. Most spots were located at groups of buildings, but also visible terrain variations were used (especially for getting a more homogenous point distribution).

A homogenous (and dense as possible) distribution of the tie points is quite important. This holds true for any estimation of transformation parameters, but it is especially important for this approach. The transformation parameters of the applied correction function (6) will be estimated by minimising the discrepancies at the tie points. The correction function, obtained this

way, will fit well in the area of the tie points (in the order the residuals after the adjustment). Because the correction function is not able to consider the dynamics of the data generation, in areas not covered by tie points extrapolation will occur (in contrast to approaches which consider the GNSS/IMU trajectory). Consequently after applying the correction function the geometric quality in these tie-less areas can not be predicted. For this reason, it is especially important for a strip adjustment without GNSS/IMU trajectory data to have a good tie point distribution.

For defining the datum of the strip adjustment three horizontal control planes and a 2D vector layer (ATKIS digital landscape model) were available. Whereas the former were usable to fix the vertical datum, the vector layer, however, contained features (street borders, embankments, etc.) which were not easy to detect in the ALS data. A visual comparison of this layer with a shading of the strip DSMs of the original georeferencing did not show any severe discrepancies (nevertheless discrepancies *between* the strips did exist). Therefore the strips should be shifted as little as possible after the adjustment. This was realised by fictitiously observing the 3D shifts  $\mathbf{a}$  to be  $(0/0/0) \pm (0.3/0.3/0.3)$  [m]. In respect of the 5 unknown parameters per strip, the datum for the adjustment is therefore defined.

#### 3.2 Adjustment results

For the datum defined in the previous subsection and the corresponding LSM points strip adjustments with different parameter setups ( $a_X, a_Y, a_Z, a_{roll}, a_{yaw}$ ) were computed: A) all parameters were fixed to be zero (this corresponds to the original georeferencing); B) the strips were only shifted; C) additionally for each strip a roll parameter  $a_{roll}$  was determined; D) as C) plus *one* yaw parameter  $a_{yaw,block}$  for the *entire* block of strips. For the variants B) and C) the fictitious observations led to large errors in the adjustment and thus had to be eliminated. For these two variants the datum was defined by fixing the horizontal shift of the strip in the centre of the block. Table 1 lists the RMS values of the residuals after the respective strip adjustment.

From the original georeferencing of the ALS data (variant A) one can clearly see a much worse horizontal accuracy compared with the height accuracy. We assume an error in the rotation component of the mounting calibration. This effects the horizontal coordinates more than the vertical one. Additionally, the flying company might have taken care of the vertical accuracy by using horizontal control fields (e.g. football fields). We also see, that already the very simple model with only 3D shifts per strip yields a *remarkable improvement of the relative orientation* of the strips (because that is was the residuals of the tie points reflect). The additional unknowns  $a_{roll}$  and  $a_{yaw,block}$  do not yield any further improvements (except in Z). Nevertheless the models B and C are not recommended at all, because they yield a *dramatic degradation of the absolute orientation*. A hint to this was already the

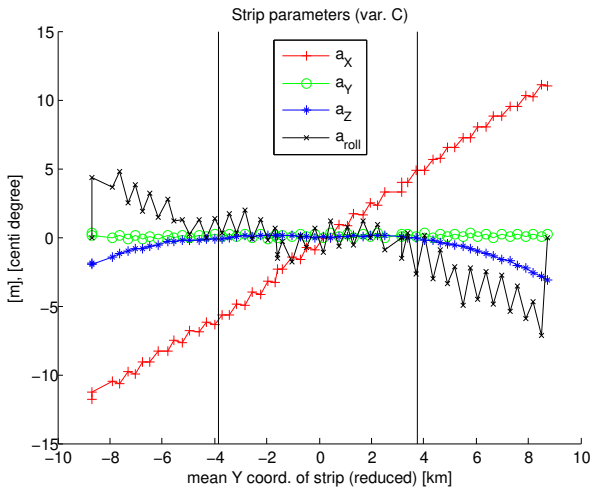


Figure 2: Plot of the transformation parameters of strip adjustment variant C: For each strip one 3D shift ( $a_X$ ,  $a_Y$ ,  $a_Z$ ) and one roll angle  $a_{roll}$  were determined. The units are meter and centi-degree, respectively. The plot is sorted by the mean Y coordinate of the strips (which were flown in X direction). The two vertical black lines bound the Y range covered by the height control planes. Most striking is the linear trend of the  $a_X$  values, ranging from -12m for the most southern strip to +12m for the most northern strip.

necessity to eliminate the fictitious observations for the 3D shifts per strip when using the models B and C. The degradation of the absolute orientation is clearly visible in fig. 2, which plots the transformation parameters determined for variant C.

This plot is arranged in order of the mean Y coordinate of the strips (from south to north). One can see clearly that both  $a_Z$  and  $a_{roll}$  are affected by a systematic degradation outside the area bound by the height control planes. This is explained by a high correlation of both parameters; i.e. outside this area over-parameterisation occurs. The most striking feature, however, is the linear trend of  $a_X$ , ranging from -12m for the most southern strip to +12m for the most northern strip; i.e. ca. 40cm per strip. Such large errors of the exterior orientation are not plausible and are in contradiction to the quality check of the absolute georeferencing by means of the 2D vector layer mentioned above.

This almost straight linear trend indicates an error in the yaw component of the mounting calibration, which is compensated by the linearly growing shift  $a_X$  in flight direction; see also fig. 3.

The little shaky pattern in fig. 2 is caused by the different flight directions and the compensation of the pitch error. The pitch error in first order approximation is almost 100% correlated with the shift  $a_X$  in flight direction (for horizontal terrain) and thus can be compensated very well by  $a_X$ . The compensation of the yaw error, however, requires an additional affine parameter  $a_{yaw}$ . This affine parameter represents the non-orthogonality between flight direction and the direction of the scanner deflection; i.e. a  $dX$  because of a  $dY$ . From the variant C results of  $a_X$  an average for this parameter was estimated to be  $a_{yaw,block} = 0.001313$  - which would correspond to an Yaw error of ca.  $0.0756^\circ$ . This average value  $a_{yaw,block}$  was introduced as a constant value for all strips in variant D.

Fig. 4 plots the transformation parameters determined for variant D. One can clearly see that the linear trend of  $a_X$  disappeared.

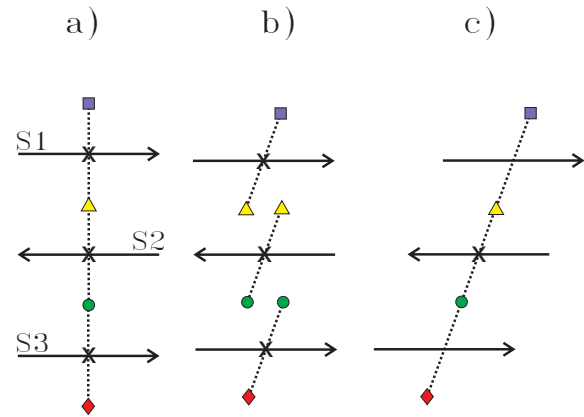


Figure 3: Effect of an error in the yaw component of the mounting calibration. For this demonstration three strips with error-free orientation are considered (a). In (b) and (c) only an error in the yaw component is introduced. The three strips S1, S2 and S3, are flown meandering in east-west direction. The 'x' indicates that the location of the strip is defined by the measured GNSS-trajectory. The other symbols (square, triangle, circle, diamond) represent measured object points (at the border of one scan line). The triangle appears in the strips (S1, S2) and the circle in (S2, S3). Description of the subfigures: **a)** all three strips depicted in the reference system with their true (i.e. error-free) orientation; **b)** an error in the yaw component of the mounting calibration is introduced (apart from that everything remains error-free); therefore the triangle and the circle in the overlap of two strips appear twice; **c)** orientation of the strips in the reference system after a strip adjustment using only one 3D shift per strip. The datum is defined by fixing the location of strip S2 (therefore only S2 is depicted with an 'x'). The uncompensated yaw error introduces a shift in flight direction linearly growing for each strip with the distance (across flight direction) from the fixed central strip.

The fictitious observations for the 3D shifts do not lead to large errors in the adjustment variant D and all strips only get shifts in the range of a few dm. The project was flown in at least three different missions. This may explain why  $a_X$  for the strips between  $Y = -4$  and  $Y = -2$  show a slightly systematic behaviour. Clearly visible in fig. 4 is the zig-zag pattern in all parameters except for  $a_Z$ . It should be caused by the usually meandering flight pattern; i.e. neighbouring strips have opposite flight directions. This was not considered because all strips were assumed to be orientated to the east. The largest zig-zag pattern is shown by  $a_X$  with changes of ca. 40cm from one strip to the other, which is the effect of the pitch correction. For large parts of the block the values for  $a_X$ ,  $a_Y$ ,  $a_Z$  and  $a_{roll}$  are quite constant, which indicates that the mounting calibration did not change much during the flight. Further a high correlation between  $a_Y$  and  $a_{roll}$  can be seen in fig. 4. In case of perfectly horizontal terrain and horizontal flight both would be correlated to 100%. Obviously the terrain is hilly enough for  $a_{roll}$  to be determinable - and as tab. 1 shows  $a_{roll}$  also has a positive effect on RMS(Z).

**Conclusion.** This example clearly demonstrates the importance of the affine parameter in flight direction for compensating the effect of a wrong yaw component of the mounting calibration. Without this parameter the strips would get unrealistic large shifts in flight direction if the strip adjustment is done without horizontal control information or cross strips. If control information and/or cross strips are available for the strip adjustment, then large discrepancies will occur at the control features in general and at the tie features in the cross strips.

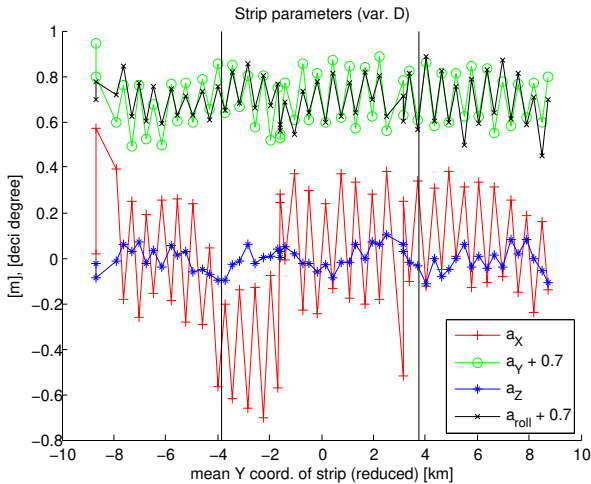


Figure 4: Plot of the transformation parameters of strip adjustment variant D: For each strip one 3D shift ( $a_x$ ,  $a_y$ ,  $a_z$ ) and one roll angle  $a_{roll}$  were determined. Additionally, one affine yaw parameter  $a_{yaw,block}$  was averaged from the  $a_x$  values of variant C and used as constant for all strips of the entire block. The units are meter and deci-degree, respectively. For better distinction the values of  $a_y$  and  $a_{roll}$  were shifted by 0.7. The plot is sorted by the mean Y coordinate of the strips (which were flown in X direction). The two vertical black lines bound the Y range covered by the height control planes. Now the linear trend of  $a_x$  visible in fig. 2 is no longer present.

### 3.3 Different accuracy check

The adjustment variant D minimized the differences between corresponding tie points in overlapping strips from (59.3/23.4/4.5) [cm] to (7.1/7.2/2.2) (RMS in (X/Y/Z)); see tab. 1. In subsection 3.1 it was mentioned that a strip adjustment approach without GNSS/IMU trajectory data cannot consider the dynamics of the data acquisition. Consequently, the geometric quality in areas not covered by tie points can not be predicted. Therefore, it would be interesting to check whether in the tie-less areas a similar accuracy gain could be also achieved. One way of showing that would be to measure another set of corresponding points (i.e. check points) in overlapping strips by means of LSM, which do not take part in the adjustment and to determine their differences before and after the strip adjustment. This would have the benefit of getting information again in X,Y,Z, but would have the drawback of delivering only discrete information (i.e. only at locations with enough surface variation for LSM).

A different way of checking the relative accuracy is to compute strip differences. For this the difference  $dZ_{pair}$  of pairs of overlapping strip DSMs is computed. Because of the interpolation involved, the differences  $dZ_{pair}$  derived at rough surface areas (e.g. vegetation) are not suitable for judging the accuracy. Thus, for statistics only  $dZ_{pair}$  determined at smooth surfaces should be considered. For this purpose the already mentioned roughness mask is used again. Fig. 5 shows the histogram of  $dZ_{pair}$  (considering the roughness mask) for the original georeferencing and for the improved one (after strip adjustment variant D). The figures 6 and 7 additionally show a color coding of these strip differences.

The strip differences  $dZ_{pair}$  have the benefit of describing the relative geometric quality in a *continuous* way (i.e. in all smooth surface parts of the project area). However,  $dZ_{pair}$  need not be computed at corresponding points. Therefore  $dZ_{pair}$  only represents the height accuracy of the ALS data if there are no horizontal errors between the strips. This is definitely not the case for the

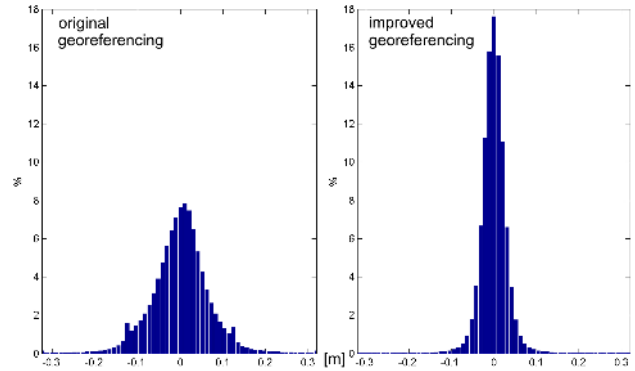


Figure 5: Histogram of the strip differences  $dZ_{pair}$  (considering the roughness mask) based on all overlapping strips (ca. 118 million values). Left: original georeferencing ( $\sigma_{MAD}=6.2\text{cm}$ ). Right: improved georeferencing after strip adjustment ( $\sigma_{MAD}=2.9\text{cm}$ ).  $\sigma_{MAD}$  is the standard deviation derived from the median of absolute differences (the so-called *MAD*) as  $\sigma_{MAD} = 1.4826 \cdot MAD$ .

original georeferencing, where we determined large horizontal errors of (59.3/23.4)[cm] between the strips. Therefore the  $\sigma_{MAD}$  value of 6.2cm listed in fig. 5 cannot be compared directly with the RMS value 4.5cm of the Z-differences (from corresponding LSM points) listed in tab. 1. However, for the improved georeferencing the horizontal RMS differences of (7.1/7.2)[cm] are very small (especially when compared with the 1m grid width of the used DSMs). Thus, there the  $\sigma_{MAD}$  value of 2.9cm listed in fig. 5 can be compared with the RMS value 2.2cm of the Z-differences from tab. 1. And both values fit very well together. The little deviation of 0.7cm can probably be attributed to the limitation of the strip adjustment approach without GNSS/IMU trajectory where remaining effects of the unconsidered flight dynamics may still be present. Because these two values fit quite well and  $dZ_{pair}$  is determined in all smooth areas of the entire project area (ca. 118 million difference values), the quality of improvement after the strip adjustment is also confirmed in the areas not covered by tie points.

## 4 SUMMARY AND OUTLOOK

This article presented a very simple model for ALS strip adjustment without GNSS/IMU trajectory data. Five parameters are used for each strip, which were specifically chosen to compensate errors of the mounting calibration: one 3D vector  $\mathbf{a}$ , one roll angle  $a_{roll}$  and one affine yaw parameter  $a_{yaw}$ .

In general a strip adjustment with GNSS/IMU trajectory data is recommended over one without. Because without it, the dynamics during the flight are not considered and the transformation equation is not rigorous.

Although a strip adjustment without GNSS/IMU trajectory data has these mentioned disadvantages and the presented model uses restrictive assumptions (terrain and flight are horizontal), the experiment with 61 flight strips demonstrated a remarkable gain in accuracy: The RMS values in (X/Y/Z) of the differences of corresponding LSM points in the overlapping strips improved from (59.3/23.4/4.5) [cm] to (7.1/7.2/2.2). Furthermore the importance of the affine parameter for compensating the error of the yaw component of the mounting calibration was demonstrated. Because without GNSS/IMU trajectory the dynamics of the data acquisition can not be considered, a homogenous and dense distribution of the tie points in the strip overlaps is very important.

The derivation of the presented model assumed horizontal terrain and a smooth flight along a straight line. In future works we

will investigate, how well this model can be applied to turbulent flights and to hilly terrain, and which adaptations are necessary to increase the applicability. For this purpose strip adjustments for different flights with given GNSS/IMU trajectory data will be computed with and without the trajectory.

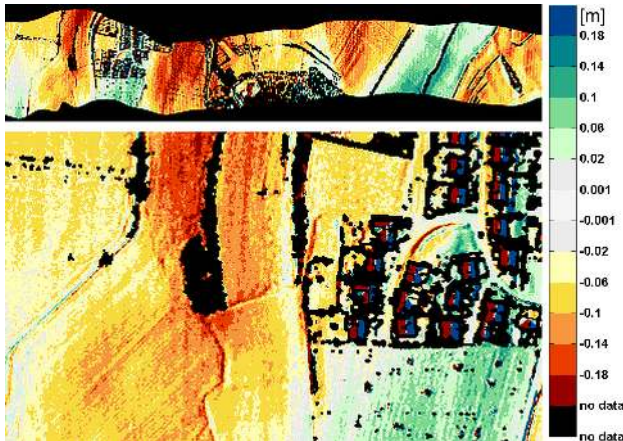


Figure 6: Strip differences for the original georeferencing. Top: Overview of a color coded difference of two overlapping strips. Bottom: Enlarged detail; observe especially the striking red and blue patterns at the roofs (with height differences beyond  $\pm 18\text{cm}$ ). These are caused by horizontal errors between the two strips. Right: Legend of color coding. Black is used for the area outside the overlap of both strips, but also for the parts covered by the roughness mask.



Figure 7: Strip differences for the improved georeferencing after the strip adjustment; cf. fig. 6. Note that the systematic patterns of the height differences, which are visible in fig. 6 (especially at the roofs), have now disappeared to a very high degree.

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