Automating the Calibration of Airborne Multisensor Imaging Systems

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Key words:

ABSTRACT

To fully exploit the potential of LIDAR technology and to consequently achieve maximum accuracy of the laser points on the ground, the entire multi-sensory measurement system should be carefully calibrated. The overall system calibration is a very complex task and includes individual sensor calibration as well as the determination of the sensors' spatial relationships. High-performance integrated GPS/INS systems provide the navigation data for the LIDAR data acquisition platform, and thus, the quality of the navigation solution is the primarily determinant of the possible accuracy of the laser spots. To achieve or approach the performance level of the navigation, however, the spatial relationship between the navigation sensor and the laser scanner, called the mounting bias or boresight, must be known with high accuracy.

This paper deals with a specific subtask of the overall system calibration process – finding the boresight misalignment of LIDAR systems. There are a few methods for obtaining the boresight misalignment, which normally refers only to the determination of the rotation angles between the INS and laser scanner systems. The most common method is a simple trial and error approach, where the operator interactively changes the angles to reach some fit of the LIDAR spots with respect to some known surface. A more advanced but still human-based technique uses block adjustment with control points. Since the ground surfaces are not always known or not at the required accuracy level, preference is given to techniques which do not require a priori knowledge of the surface. In this paper we propose an automatic boresight determination method that does not require any ground control and is based on using two/three or more overlapping LIDAR strips flown in different directions. The surface differences from the different strips over the same area are considered as observations and an adjustment is formulated to determine the boresight misalignment angles.

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INTRODUCTION

In recent years, direct orientation has become a powerful and efficient way in mainstream airborne surveying of obtaining sensor orientation by direct physical measurements. The GPS/INS sensor-based methods can provide aircraft position within sub-decimeter accuracy and attitude within the 20-30 arcsec range (Abdullah, 1997; Toth, 1998; Brzezinska, 1999; and Cramer, 2000). In traditional analog film-based surveying, this accuracy level of the exterior orientation parameters can almost totally eliminate the need for aerial triangulation in the production workflow, which is one of the most complex and time-consuming tasks in photogrammetry. The use of GPS/INS-based positioning technology, however, is mandatory for LIDAR systems and very beneficial for the emerging digital camera systems such as frame or three-line cameras acquiring monochrome and/or multi/hyperscectral imagery.

LIDAR systems are complex multi-sensory systems and include at least three main sensors, GPS and INS navigation sensors, and the laser-scanning device. The laser system measures the distances from the sensor to the ground surface. The coordinates of the ground point from where the laser pulse returned can be calculated if the travel distance of the laser pulse, the laser beam orientation and the position of the laser scanner are known. Various things such as positioning errors, e.g. temporary GPS anomalies and/or misalignment between the laser and navigation systems can cause a misfit between the LIDAR points and the true surface or a difference between surfaces obtained from two LIDAR strips covering the same area. In general, the lack of feedback in the data flow in LIDAR systems makes the whole system more vulnerable to systematic errors and that seriously affect the quality of the LIDAR data. Baltsavias (1999) presents an overview of basic relations and error formulas concerning airborne laser scanning and a large number of publications report the existence of systematic errors. The solution for dealing with and eliminating the effect of systematic errors can be categorized into two groups. One approach is based on the introduction of a correction transformation of the laser points to minimize the difference between the corresponding LIDAR patches and ground truth. Kilian (1996) presents a method of transforming overlapping LIDAR strips to make them coincide with each other using control and tie points in a similar way to photogrammetric block adjustment. The other technique attempts to rigorously model the system to recover the systematic errors. Burman (2000) treats the discrepancies between overlapping strips as orientation errors, with special attention given to the alignment error between the INS and laser scanner. Filin (2001) presents a similar method for recovering the systematic errors with respect to the boresight misalignment problem.

This paper describes a method to automate the boresight misalignment of LIDAR systems. The developed technique is based on the availability of multiple overlapping LIDAR strips over an unknown surface, although ground truth is also used if available. The surface where the LIDAR strips overlap must have certain characteristics in order to make the process work. There should be observable horizontal and vertical discrepancies between the different

LIDAR datasets but extreme variations in height as well as densely-vegetated or wooded areas should be avoided. Finally, the LIDAR strips should be flown in certain pattern as discussed later.

BORSIGHT MISALIGNMENT

Figure 1 shows the usual sensor configuration of airborne LIDAR systems. The navigation sensors are separated the most since the GPS antenna is installed on the top of the fuselage while the INS sensor is attached to the LIDAR system, which is down in the aircraft. The spatial relationship between the sensors should be known with high accuracy. In addition, maintaining a rigid connection between the sensors is also very important since modeling any changes in the sensor geometry in time just would further increase the complexity of the system model and thus may add to the overall error. The INS frame is usually considered as the local reference system; thus the navigation solution is computed in this frame. The spatial relationship between the laser scanner and the INS is defined by the offset and rotation between the two systems. The critical component here is the rotation since the object distance amplifies the effect of an angular inaccuracy, while the effect of an inaccuracy in the offset does not depend on the flying height. The description of the effects of the different boresight misalignment angles is omitted here; for details see e.g. (Baltsavias 1998).

The coordinates of a laser point are a function of the exterior orientation of the laser sensor and the laser range vector. The observation equation is:

$$r_{M,k} = r_{M,INS} + R_{INS}^{M}(R_{L}^{INS} \cdot r_L + b_{INS}) \tag{1}$$

where

$r_{M,k}$	—	3D coordinates of point k in the mapping frame
$r_{M,INS}$	—	3D INS coordinates in the mapping frame
R_{INS}^{M}	—	rotation matrix between the INS frame and mapping frame, measured by GPS/INS
R_{L}^{INS}	—	boresight matrix between the laser frame and INS frame
r_L	—	3D object coordinates in laser frame
b_{INS}	—	boresight offset component

To obtain the local object coordinates of a LIDAR point, the laser range vector has to be reduced to the INS system by applying the shift and rotation between the two systems, which results in the coordinates of the LIDAR point in the INS system. The GPS/INS-based navigation provides the orientation of the INS frame, including position and attitude; thus the mapping frame coordinates can be subsequently derived. In our discussion, the automated determination of the rotation component, the boresight matrix between the INS and the laser frame, is addressed.

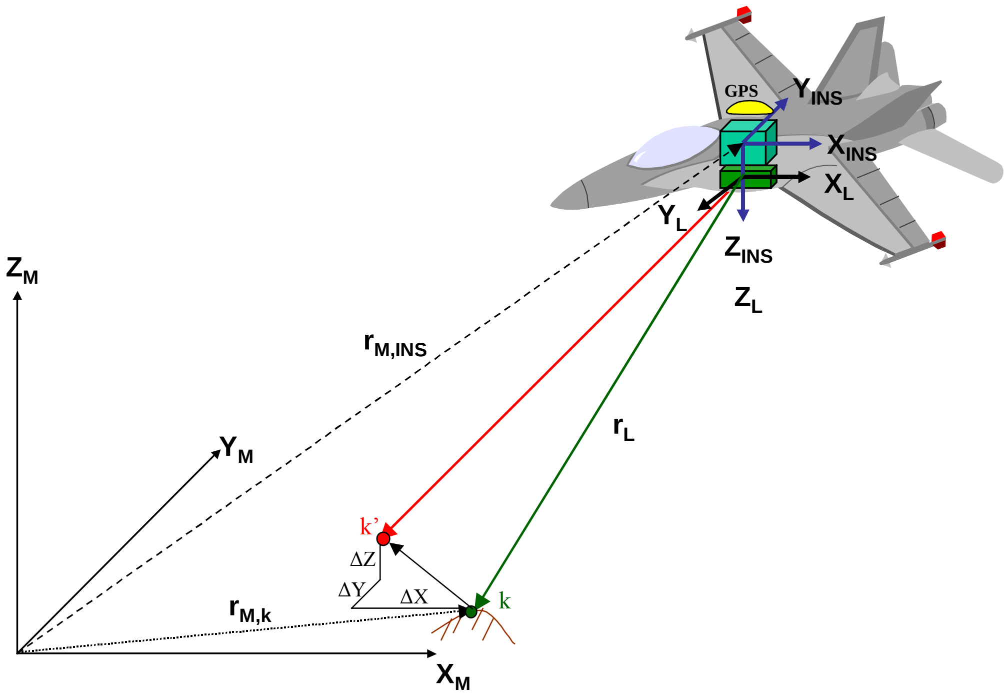

Figure 1. LIDAR system sensor configuration.

The boresight rotation can be described by three rotation angles, ω rotation around the x-axis, φ rotation around the y-axis, and κ around the z-axis in the laser sensor frame. The approximate values of the three rotation angles between the INS and the laser frames are known from the mechanical alignment. The actual angles differ slightly from these nominal values. The boresight misalignment problem is to determine these three misalignment angles. Any discrepancy in their values results in a misfit between the LIDAR points and the ground surface; the calculated coordinates of the LIDAR points are not correct. In case the ground surface is unknown, the effect of the misalignment can be seen if different overlapping LIDAR strips are flown in different directions. Figure 2 shows a situation where the overlapping strips do not fit each other; the horizontal and vertical discrepancies can be substantial at high flying altitudes.

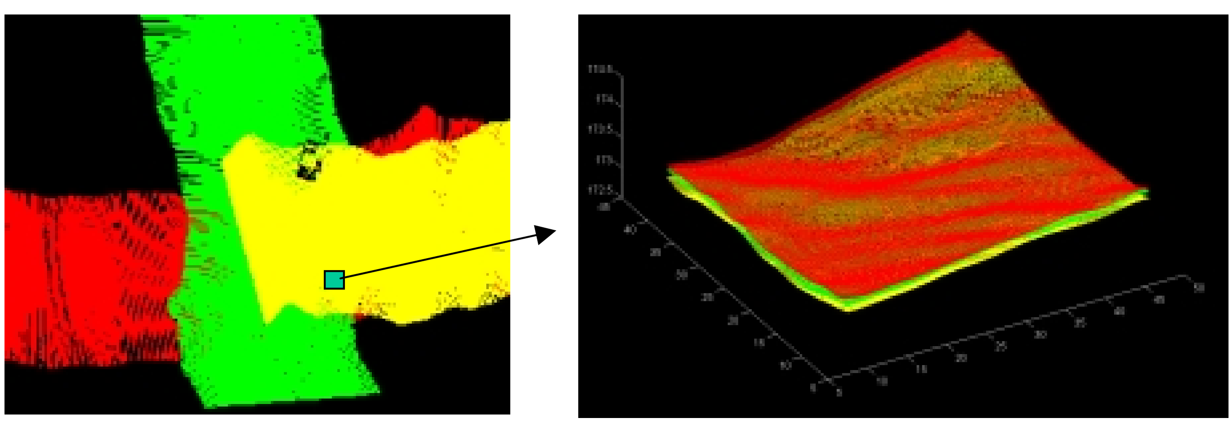

Figure 2. Overlapping LIDAR strips.

Boresight misalignment has to be determined to obtain correct surface from the LIDAR data. The unknown boresight misalignment angles can be found with ground control or without it by using overlapping LIDAR strips flown in different directions. Since the true ground surfaces are not always available preference should be given to techniques that do not require a priori knowledge of the surface.

CONCEPT OF THE BORESIGHT MISALIGNMENT DETERMINATION

The proposed method requires overlapping LIDAR strips. The more strips are used, the more reliable the results are. Without ground control, the horizontal and vertical discrepancies between the strips are used to determine the unknown misalignment angles. Therefore, appropriate portions of the overlapping area have to be selected for observing surface differences. The ideal portions for this purpose are near the borders of the overlapping area, where the differences are more noticeable, like the Gruber point distribution in stereo photogrammetry. Comparing different surfaces, formed by randomly scattered points is a non-trivial task and the effectiveness of this process depends a lot on the point density of the LIDAR points and on the overall terrain characteristics of overlapping area. A frequently used technique is interpolation into a regular grid. Then the discrepancies can be determined relatively easily by surface matching of the selected regions or profile matching of man-made objects, etc. Once the surface differences are known at certain regions of the overlapping area, a least squares adjustment can be formed for the unknown misalignment angles. In this discussion, the main steps are introduced briefly, and only the last step, the adjustment of the boresight angles is discussed in detail.

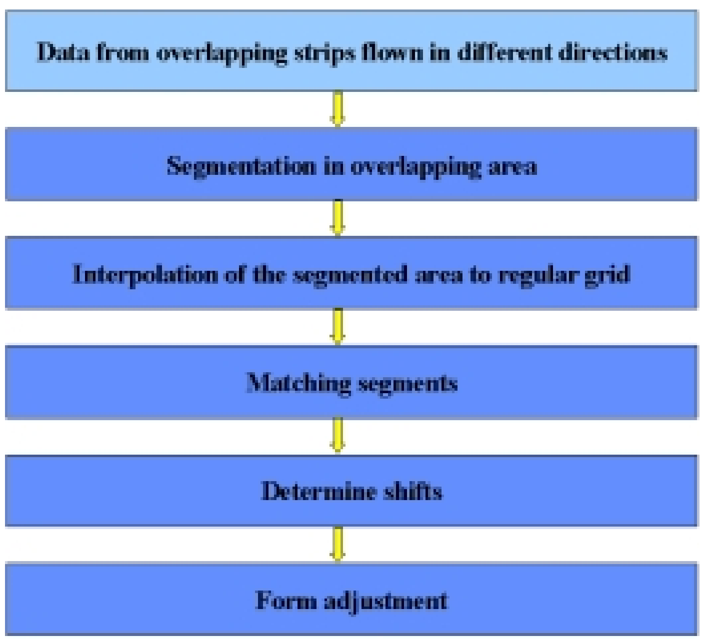

Figure 3. Concept of boresight misalignment determination.

Segmentation

Segmentation is the process of selecting appropriate areas for obtaining reliable surface difference values. Forested areas, complex buildings and moving objects are to be avoided. Smoothly rolling terrains, however, are ideal areas since they exhibit only limited undulations, so differences can be observed yet their surface representation does not require excessive spatial sampling. These types of areas can effectively cope with various LIDAR configurations, coming from different flying heights, pulse repetition rates, scan angles and flying speeds, all resulting in different point patterns and point densities. From the potentially viable segments, a few should finally be selected based on their closeness to the overlapping area boundary and for their even distribution.

Interpolation

Various surface interpolation methods exist and are used in practice to deal with irregularly spaced surface points or to convert them into a regular grid. Most techniques are based on a TIN model, although many others techniques are also reported in the literature see e.g. (Sarkozy, 1998). After testing some of the commonly used methods, we found that the local methods such as weighted average interpolation where the unknown values are calculated from the surrounding known points are not appropriate for the interpolation of the sparse LIDAR data (in our investigations, we were primarily concerned with LIDAR surveys conducted at regular or higher flying height). Similarly, global methods such as polynomial interpolation may provide a better approximation of the LIDAR surface, but these do not adequately represent smaller changes of the surface. Consequently, we decided on an interpolation method that would combine Fourier-series and polynomial models. In the first step, a least squares adjustment was formulated for determining the Fourier-series coefficients. Since the discrete Fourier-series is based on evenly-spaced data, it cannot be directly applied to approximate surfaces from irregularly scattered LIDAR points as the coefficients of the Fourier-series cannot be calculated in the usual way. Thereafter, the model was extended to include polynomial coefficients. In our experiences, the combined model has shown a promising performance, as the polynomial components seemed to preserve the overall trend of the surface while the Fourier component appeared to adequately handle the smaller local changes. Figure 4 shows a small surface modeled by the combined method.

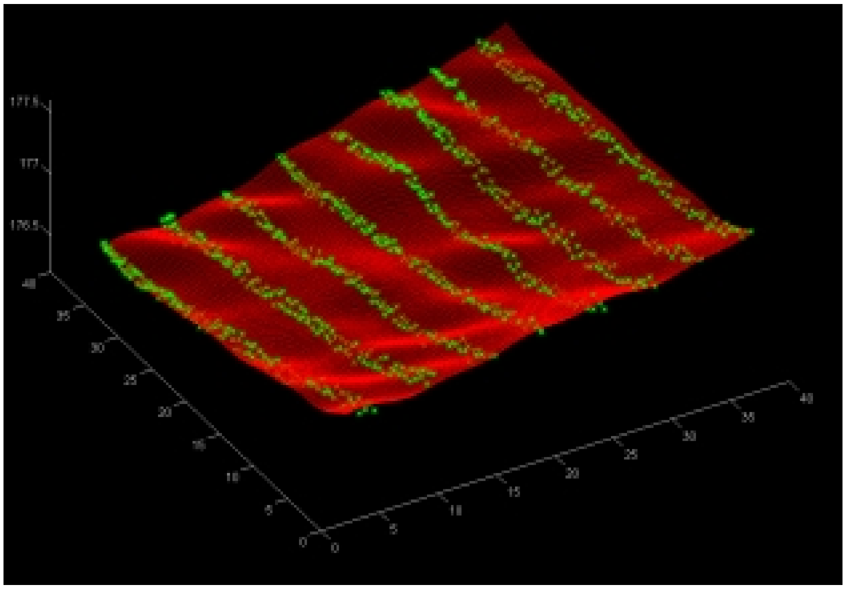

Figure 4. Fourier-series and third order polynomial interpolation of LIDAR data.

Matching

Matching in our context is the process of finding the differences in all three dimensions between the selected and interpolated small segments of the overlapping area. These offset values can be formed between any pairs of LIDAR data strips. Matching in general is an extremely broad topic. Although the number of image matching methods is almost countless, most of them are based on correlation or gradient discrepancies (Sun, 1998). A popular method in mapping is least squares matching, introduced by Gruen (1985), which usually delivers excellent results provided that good initial approximations are available. The reliability of the matching of LIDAR points depends primarily on the point density, which, in turn, depends on many factors such as flying height or swath width. Our investigation is concerned with relatively high flying height surveys, where the laser point density is rather low, which results in less reliable matching. During our tests, correlation matching was used primarily to determine the discrepancies of overlapping LIDAR strips. The results were mixed and this task needs further research effort to achieve consistent performance.

THE PROPOSED ADJUSTMENT METHOD

The proposed adjustment method is based on the observation equation (1) and is concerned only with the rotation angles between the INS and laser systems. The offset components are ignored since their inaccuracy is negligibly small both in absolute terms and compared to the effect of any inaccuracy in the rotation angles between the two systems. This results from the fact that the effect of an angular inaccuracy is amplified by the object distance, while the effect of an inaccuracy in the offset does not depend on the flying height.

The principle behind this method is very simple. Based on the observed differences, the misaligment angles are iteratively adjusted to reduce the surface discrepancies in object space. To apply the boresight misaligment and thus to correct the LIDAR point coordinates in object space, all the terms of the observation equation should be known. Therefore, the sensor platform orientation should be known for each laser point. Obviously, this is not really a strict condition since this information is always available by definition. Finding the surface differences, however, is a less than trivial task as it was briefly discussed earlier. Figure 5 shows the main steps of the adjustment method. To partially compensate for the uncertainty of the matching, a refinement has been included such that with the initial boresight misalignment results, the surface differences are recalculated and the whole adjustment process is repeated.

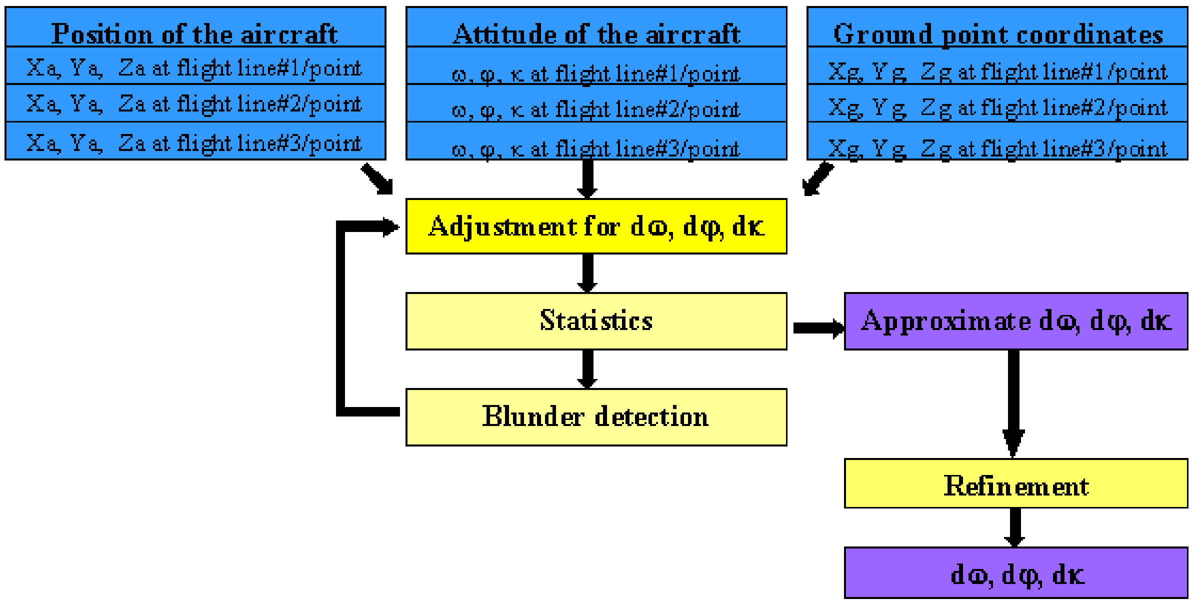

Figure 5. Main steps of the adjustment.

The adjustment process starts by taking the surface differences, which are expressed as matched virtual laser points. These points are determined a priori for all the surface patches of the overlapping area. Besides their coordinates, the orientation of the data acquisition platform, including position and attitude, is required. In addition, the coarse boresight angles and weights for vertical and horizontal control can be specified. The concept is to eliminate the surface differences by estimating the correct rotation angles between the INS and laser systems. Without proper boresight alignment, the calculated ground coordinates of a laser point or the surface they represent will be different in the overlapping area. The coordinates, however, can easily be corrected by rotating the range vector by the corrected boresight angles (R_L^{INS}) in the laser frame.

$$\begin{bmatrix} X_g \\ Y_g \\ Z_g \end{bmatrix}^{corr} = R_{INS}^{M} R_L^{INS} \begin{bmatrix} X_g \\ Y_g \\ Z_g \end{bmatrix}^{L} + \begin{bmatrix} X_a \\ Y_a \\ Z_a \end{bmatrix}^{M}$$

Where

$$\begin{bmatrix} X_g \\ Y_g \\ Z_g \end{bmatrix}^{corr}$$ are the corrected ground coordinates in the mapping frame,

R_{INS}^{M} is the rotation matrix between the INS and mapping frame,

$$\begin{bmatrix} X_g \\ Y_g \\ Z_g \end{bmatrix}^{L}$$ is the range vector in the laser system,

$$\begin{bmatrix} X_a \\ Y_a \\ Z_a \end{bmatrix}^{M}$$ are the laser frame coordinates in the mapping frame at the time of measuring the ground point.

If the coarse boresight angles are zero, the R_L^{INS} matrix only contains the unknown boresight misalignment angles. Since the boresight misalignment angles are differential small angles, the rotation matrix can be written in the usual differential form:

$$R_L^{INS} = \begin{bmatrix} 1 & -d\kappa & d\varphi \\ d\kappa & 1 & -d\omega \\ -d\varphi & d\omega & 1 \end{bmatrix}$$

For non-zero coarse boresight misalignment angles, the R_L^{INS} matrix contains the (ω+dω), (φ+dφ), (κ+dκ) rotation angles.

For two overlapping LIDAR strips, the boresight angles can be found using the fact that the matched virtual points in the two strips should have the same coordinates, so the difference between the corrected coordinates should be zero. Three equations can be formed at each pair of points, which together contain the unknown three boresight misalignment angles.

$$\begin{bmatrix} X_g \\ Y_g \\ Z_g \end{bmatrix}_1^{corr} - \begin{bmatrix} X_g \\ Y_g \\ Z_g \end{bmatrix}_2^{corr} = R_{INS1}^{M} R_L^{INS} \begin{bmatrix} X_g \\ Y_g \\ Z_g \end{bmatrix}_1^{L} + \begin{bmatrix} X_a \\ Y_a \\ Z_a \end{bmatrix}_1^{M} - R_{INS2}^{M} R_L^{INS} \begin{bmatrix} X_g \\ Y_g \\ Z_g \end{bmatrix}_2^{L} - \begin{bmatrix} X_a \\ Y_a \\ Z_a \end{bmatrix}_2^{M}$$

The navigation data of the matched virtual points are either known or can be interpolated using the navigation data of the surrounding laser points. If n overlapping strips are flown, 3n equations can be formed at each matched virtual point. In this case, the unknown boresight misalignment angles can be found using least squares adjustment (Detrekoi, 1991) with the condition that the square sum of the differences between the corrected coordinates of the matched virtual points in the different strips is minimum. For the typical three overlapping strips case, the following equation can be formed:

$$M = \sum_{1}^{m}\left(\Delta X_{12}^{2} wh + \Delta X_{13}^{2} wh + \Delta X_{23}^{2} wh + \Delta Y_{12}^{2} wh + \Delta Y_{13}^{2} wh + \Delta Y_{23}^{2} wh + \Delta Z_{12}^{2} wv + \Delta Z_{13}^{2} wv + \Delta Z_{23}^{2} wv \right) \rightarrow \min$$

where m is the number of matched virtual points. Since the vertical matching results are usually more reliable than the horizontal ones, more weight is preferable for the vertical coordinate difference residuals (*wv*) than for the horizontal ones (*wh*). As a consequence, the roll misalignment will be more reliable than the pitch or heading components.

As a standard procedure, at the end of the adjustment the residual coordinate differences between the strips at the matched virtual points are calculated. Then after removing the points with big residuals, the adjustment process starts all over again. Large residuals are mainly caused by blunders in the input data, typically due to gross matching errors. As another step in dealing with the matching uncertainty, the whole matching process is repeated on the boresight misalignment corrected data as the differences should be smaller and thus better matching performance is expected.

EXPERIENCES

The developed method for boresight misalignment has been implemented in a Matlab environment. In addition, in house C++ software modules as well as generic programs have been used to realize some of the required processing tasks. In the first phase, extensive simulations were performed to check implementation correctness and to validate the performance potential. After some fine-tuning of both the algorithm and its implementation, tests were carried out on real datasets. For the purpose of illustration, a project with a higher than usual boresight alignment error has been selected for our discussion. The data was acquired over the Dallas, TX area and the flying height was about 3,500 m with a point density of about 0.1 point/m². Six patches with an approximate size of 100 m by 100m have been selected from the 3-strip overlapping area, as shown in Fig 6.

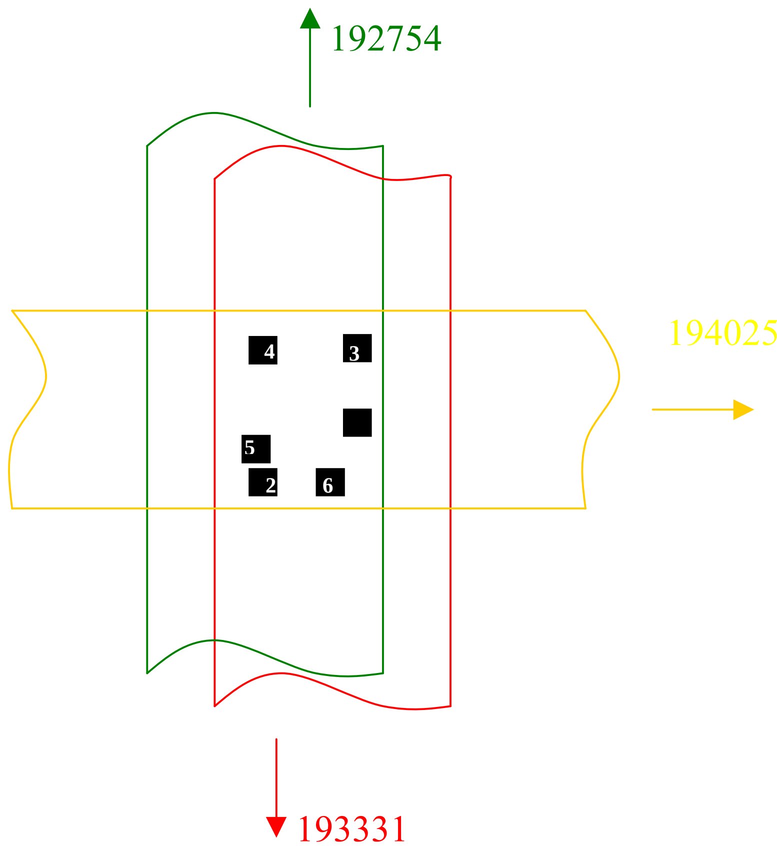

Figure 6. Overlapping strips of the test data set with the six patches.

During the preprocessing phase, about 50 virtual matching points were created for each patch. Then the adjustment process was performed separately for the 6 selected patches and also for all 6 patches (291 points). Table 1 contains the results of the seven adjustments and the operator determined values. The roll and pitch values of all the seven adjustments are practically the same as the operator derived values; the difference is a few arc seconds. Obviously, the adjustment including all the patches delivers the best results, but the individual adjustments of the patches have performed remarkably well, which is probably due to the large patch size and to the large number of points within the patch.

Adjustmen t #	Patch included	Number of points	First		
			dω [rad]	dφ [rad]	dκ [rad]
1	1	22	-0.00414	-0.01294	0.00053
2	2	63	-0.00408	-0.01306	-0.00535
3	3	51	-0.00398	-0.01268	0.00592
4	4	61	-0.00410	-0.01248	0.00650
5	5	43	-0.00405	-0.01307	-0.00499
6	6	51	-0.00391	-0.01296	-0.00552
7	1,2,3,4,5,6	291	-0.00403	-0.01281	-0.00270
Operator			-0.00404	-0.01303	

Table 1. Boresight misalignment results vs. operator derived values.

Figure 7 shows LIDAR profiles – in fact, several profiles bundled together – to visually illustrate the difference between before and after the boresight misalignment has been applied. The three LIDAR strips are color-coded and the difference in the displayed Y ground direction was originally about 40 m. However, this difference subsequently went down to the meter level after applying the boresight misalignment correction (remember that this project having extreme characteristics was intentionally selected).

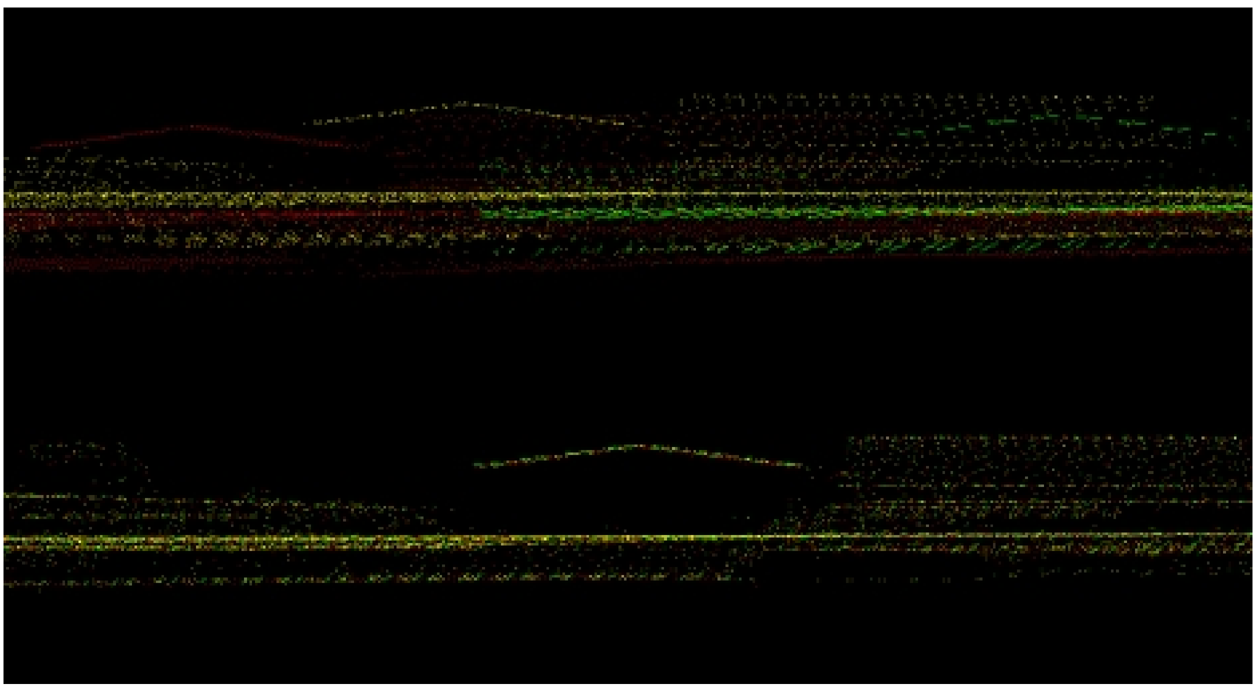

Figure 7. LIDAR profiles before and after the boresight misalignment has been applied.

CONCLUSIONS

LIDAR systems have to be well calibrated to deliver accurate three-dimensional coordinates of the measured ground surface. Boresight misalignment as part of the overall multi-sensor system calibration problem is a source of systematic errors and thus can cause a mismatch between datasets obtained from different LIDAR strips or ground truth. The impact of these discrepancies is especially significant for higher flying height surveys.

In this paper, a new method has been introduced to automate the determination of the boresight misalignment angles. Boresight misalignment can be determined provided sufficient ground control is available. In lack of ground control, overlapping LIDAR strips can be used to achieve the same results. The developed method is based on the differences observed between the overlapping LIDAR strips and requires navigation data. Results from simulations and real datasets have shown encouraging performance. For not too complex areas, the solution is robust and there is very little dependency on the performance of matching – the process of finding the surface discrepancies. For feature-rich areas such as densely built-up urban areas or wooded areas, the current performance of matching may not be sufficient, although the adjustment will work for operator-based observations too. As a future research task, the method can be extended to model other LIDAR-related errors such as variable scan angle error (smiley error).

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