Post-mission Adjustment Methods of Airborne Laser Scanning Data

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Key words: ALS, LIDAR, adjustment, calibration, laser scanner.

ABSTRACT

Airborne Laser Scanners (ALS) offer high speed, high accuracy and quick deployment in the field. These attributes have contributed to their growing use. To date however, there has been a lack of common calibration methods; especially on the commerical market. Users are often left to develop their own methods which is time consuming and labour intensive. This paper reviews the effects of miscalibration on the derived terrain data, covers current methods of calibration and suggests a new adjustment model that allows for the parameterization of ALS scanner errors. Using data from a Leica Geosystems ALS40, the results of the new adjustment model show that a calibration solution can be obtained without the need of surveyed ground control points. Other results indicate that tie point selection is an important factor on the quality and consistency of the calibration model.

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INTRODUCTION

Airborne Laser Scanning (ALS) systems are gaining in popularity due to their high accuracy, quick deployment and delivery and high automation. Multiple products such as bald Earth, forest stand counting and building delineation can be automatically extracted from a single dataset (Axelsson 2000). ALS systems are relatively lightweight and can be deployed in standard aircraft (Leica Geosystems 2002). As more systems operate however, the demand for standard solutions to common operating issues is increasing. These demands include post-processing software and calibration/alignment issues. While commercial products have begun appearing for post-processing (Terrasolid 2002, Leica 2002), many users are left to develop their own methods for calibration; which can be both a time consuming and knowledge intensive operation. This paper will review some current methods of ALS calibration, and report on an ongoing project to automate the calibration of several major parameters.

CALIBRATION ERRORS

ALS systems are the combination of several surveying technologies. While there are differences between commercial systems, the basic package remains the same: a Global Positioning System (GPS) receiver and an Inertial Navigation System (INS) as the navigation component, and laser range finder and a scanner as the remote sensing component (Wehr 1999). Each component requires calibration and the offsets between the components needs to be determined. GPS/INS and range finders are usually calibrated in the lab; thus this paper will concentrate on scanner and misalignment (bore sight) values.

The misalignment between the INS system and the scanner is the largest source of systematic error in an ALS and must be addressed before the sensor can be effectively deployed. It has been observed empirically that these misalignment errors are often relatively small (0.1 – 3 degrees), but their effect on the recorded ground points will depend on flying height and the scanner field of view (maximum scan angle) (Burman 2000b). When comparing data from overlapping strips on an un-calibrated system, the effects of these errors will be seen as in Figure 1 (next page):

On systems using an oscillating scanner (such as the Leica ALS40 and the Optech ALTM), additional errors can be visible when comparing strips (Crombaugh et al. 2000) (Figure 2):

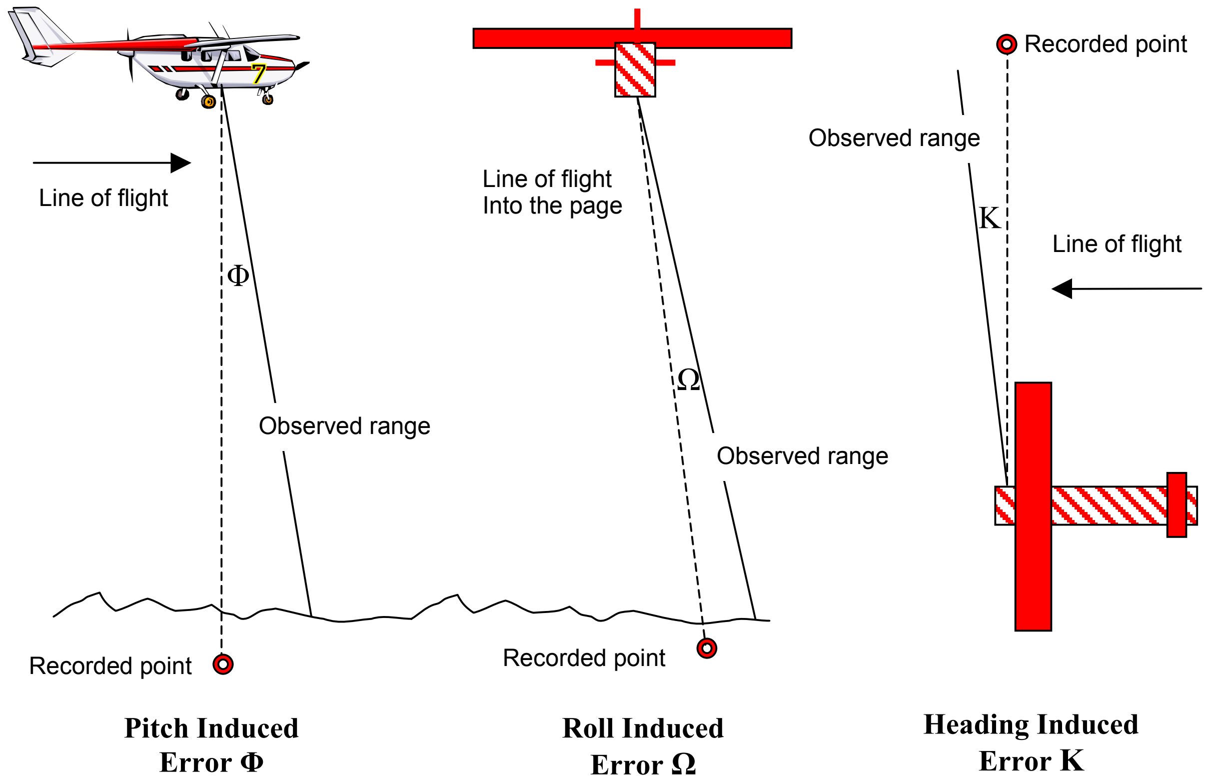


Figure 1: Boresight Induced Errors

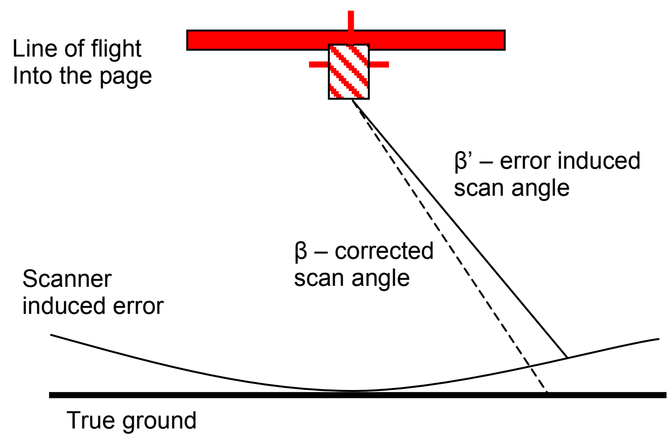


Figure 2: Scanner Induced Errors

These additional effects are caused by errors in the angle encoder. As the mirror accelerates and decelerates across its swath, the angle encoder undergoes small amounts of torsion. This torsion causes a small, but systematic misreading of the angle, which is manifested by the ends of the scan rising too high or dropping too low. Due to the systematic nature of this error, it can be modeled and removed during the calibration process.

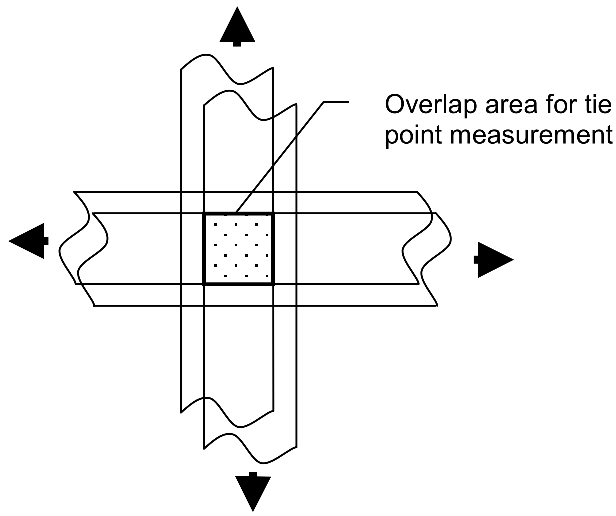


Figure 3: Desired ALS Data for Calibration Testing

To determine the calibration parameters empirically, data from overlapping strips must be collected. Alternatively, data from one strip can be compared to a known surface. The misalignment errors and scanner errors described above are all correlated with the direction of flight. If strips are flown in opposite directions, then the induced errors will be maximized and more importantly de-correlated (Burman 2000b). This will allows for a least-squares approach to the problem.

CALIBRATION METHODS

Currently the most common method of calibrating an ALS sensor is also the least rigorous: profiles of overlapping strips are compared and an experienced operator manually adjusts the misalignment angles until the strips appear to visually fit. Although pragmatic, this approach is time consuming and labour intensive; and the results do not immediately provide any statistical measure on the quality of the calibration.

More rigorous methods begin with the observation that the ALS misalignment problem appears to be no more than a classical photogrammetric problem in which the coordinates of the observed points need to be transformed into a target reference frame, i.e.:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{\substack{target \\ frame}} = R_{\substack{observation \\ to \\ target \\ rotation}} \cdot R_{misalignment} \cdot \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{\substack{observation \\ frame}} \qquad \textbf{(1)}$$

A user should be able to determine the value of the misalignment matrix by using surveyed control points and inverting the solution. Unfortunately with ALS data, this is not a trivial task. Unlike photogrammetry, the data is not collected on a frame or strip basis but rather point-by-point; and for each point, the aircraft is at a new position and orientation. The points are distributed in a pseudo-random manner along the scanner path (typically a Z shape for oscillating scanners) – the user has no control over what the laser hits; thus signalized control points are difficult to observe. As the laser propagates through the atmosphere, the beam diverges. When its hits the ground it can be in excess of 30 cm in diameter – thus measuring edges is difficult as well.

In spite of these difficulties, several methods have been developed to help determine tie points between ALS strips and allow for a least-squares adjustment using Eq 1. The simplest way of collecting tie points is to measure them manually in a digital photogrammetric suite. The random points are gridded and then represented in a raster form. The user picks off common features between the strips or attempts to measure known control points (Kilian, J, Haala, N., Englich, M, 1996). This method depends on an experienced user and is time consuming; but when used with a least-squares adjustment, produces results that can be statistically analyzed.

The next evolution to this method is to employ an automated area matching technique to pick out common features between strips. This method (Burman 2000a) relies on areas with high gradients in the data to provide a sharp signal to match. When using elevation data alone however, this is a problem due to the poor edge-capture ability of ALS systems. This can be partially addressed by matching patches (Maas 2000). To improve results further, Maas and Vosselman (2000) matched patches directly from a Triangulated Irregular Network (TIN) structure holding the raw ALS observations. This method provided good matching of points, but automatically determining a feature from elevation data alone was still problematic.

Another approach to tie point selection is to match features such as entire buildings or roadways (Morin and El-Sheimy, 2001a). Rather than relying on a small set of observations, features are parameterized using large numbers of observations to increase the accuracy of the feature models. Common features can then be compared in the latter ALS adjustment to determine the calibration parameters.

ADJUSTMENT MATH MODELS

Each ground or tie point from an ALS can be described as a parametric equation, as follows:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{\substack{ground\\control}} = \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{\substack{aircraft\\position}} + R_{\substack{body\\frame\\to\\ground\\rotation}} \cdot R_{misalignment} \cdot \begin{pmatrix} l_x \\ l_y \\ l_z \end{pmatrix}_{\substack{laser\\range\\components}} \tag{2}$$

where:

$(X,Y,Z)_{ground\ control}$	is the derived terrain point
$(X,Y,Z)_{aircraft\ position}$	is the aircraft position at the observation epoch
$R_{body\ to\ ground\ rotation}$	is the rotation cosine matrix from the aircraft body frame to the ground frame
$(l_x,l_y,l_z)_{laser\ range}$	are the laser range components derived from the laser range and scanner angle.

The solution to $R_{misalignment}$ can be found by using the ALS observations (aircraft position, body frame rotation, laser range) and surveyed control points (X,Y,Z). The values for $R_{misalignment}$ can be solved using a standard least-squares method. If $R_{misalignment}$ were a cosine direction matrix containing the full sin and cosine terms, then the solution would be non-linear and it would need to be iterated to obtain the misalignment parameters. As noted earlier however, it has been seen empirically that the misalignment angles are often < 3 degrees. The misalignment matrix $R_{misalignment}$ can therefore be replaced by a small-angle approximation:

$$R_{misalignment} = \begin{pmatrix} 1 & -\kappa & \phi \\ \kappa & 1 & -\omega \\ -\phi & \omega & 1 \end{pmatrix} \tag{3}$$

where:

ω,ϕ,κ	are the roll, pitch and heading misalignment angles

This matrix is linear with respect to the unknowns, which results in a direct solution of the misalignment angles without iteration or the need for an initial approximation.

Equation 2 relies on surveyed ground control points to perform the adjustment. Although this may be practical when operating a sensor from a home base, a solution that does not require control points is highly desirable to allow for a more generic calibration method that can be used in the field. This can be achieved by replacing the control points with the constrained average of the tie point observations. This method assumes that the average value of a single point, observed in multiple strips will approximate the true location of the point. This assumption is only valid if the strips were collected in such a way that the errors are de-correlated (as described in Calibration Errors). The new model is similar to Equation 2,

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{\substack{average \\ tiepoint}} = \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{\substack{aircraft \\ position}} + R_{\substack{body \\ frame \\ to \\ ground \\ rotation}} \cdot R_{misalignment} \cdot \begin{pmatrix} l_x \\ l_y \\ l_z \end{pmatrix}_{\substack{laser \\ range \\ components}}$$

$$where: \tag{4}$$

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{\substack{average \\ tiepoint}} = \left(\frac{1}{n}\right) \begin{pmatrix} \sum X_{tiepoint} \\ \sum Y_{tiepoint} \\ \sum Z_{tiepoint} \end{pmatrix}$$

where:

n is the number of points used to parameterize the tie point

This model must be iterated so that the average constraints are updated for each correction of the calibration parameters. This method allows the tie points in the different strips to converge to a common point without the need for surveyed ground control.

Due to the random nature of the ALS ground point observations, data entered in the least-squares equations is usually interpolated rather than a true observed point. Any point within the coverage area can be indexed by time and referenced to the aircraft position. From there the theoretical values for laser range and scanner angle can be computed. The interpolated observations are suitable for adjustments that solve for bore sight angles only, but when scanner corrections are modeled, this method begins to break down. Scanner corrections are dependent on scanner position and acceleration. Although a scanner position can be interpolated for a tie point, acceleration cannot be. Only true observations can be used to model scanner errors, thus true observations must appear in the adjustment model.

The new model proposed here addresses the need for true observations by incorporating the tie point interpolation within the adjustment model. The methodology begins by searching out the nearest true observations of the collected tie point within the ALS dataset. The tie point is then parameterized as a function of distances from the nearest true points, i.e.:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{tiepoint} = \left(\frac{1}{n}\right)\begin{pmatrix} \sum X_{observed} + dx \\ \sum Y_{observed} + dy \\ \sum Z_{observed} + dz \end{pmatrix} \tag{5}$$

where:

dx,dy,dz are the intial distances between the measured tie point and the uncorrected, observed ALS ground point.

$(X,Y,Z)_{observed}$ are the updated ALS ground points using Equation 4.

The averages can be simple or inverse distance weighted. The observation equation for the adjustment then changed to:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{\substack{average \\ tiepoint}} = \left(\frac{1}{n}\right)\cdot\sum_{i=0}^{n}\left[\begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{\substack{aircraft \\ position}} + R_{\substack{body \\ frame \\ to \\ ground \\ rotation}} \cdot R_{misalignment}\cdot\begin{pmatrix} l_x \\ l_y \\ l_z \end{pmatrix}_{\substack{laser \\ range \\ components}} + \begin{pmatrix} dx \\ dy \\ dz \end{pmatrix}_{\substack{tiepoint \\ distances}}\right] \tag{6}$$

Although a single tie point observation equation now contains several ALS observations, they are a linear combination and the partial derivatives for the design matrices are just the weighted average of the partial derivatives of each observation.

In addition to the misalignment parameters, corrections for scanner errors are also included in the laser range components vector. These parameters correct the scan angle for the latency and acceleration effects. Models vary from system to system and are generally kept internal to the system. The scanner correction model used in this project has 2 parameters.

TEST DATA

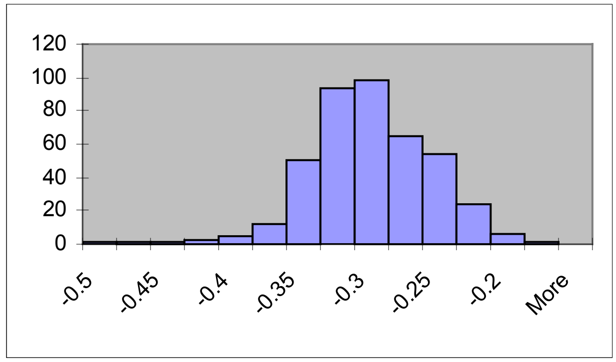
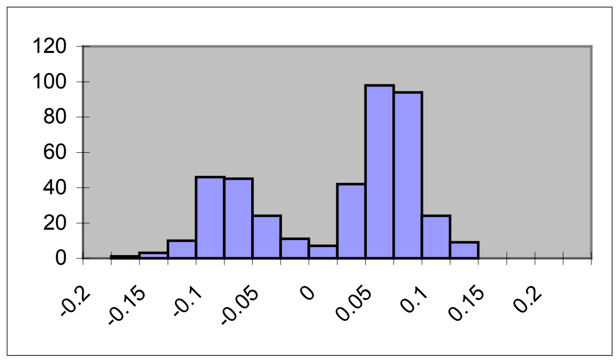
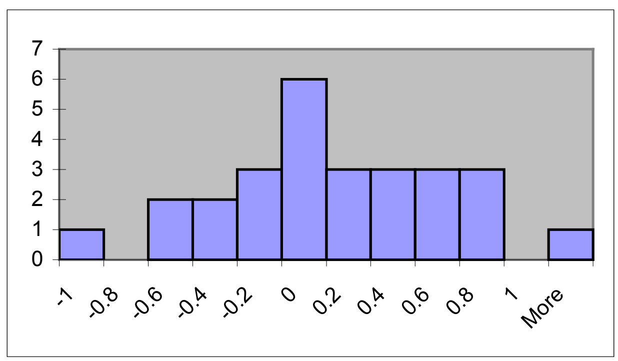
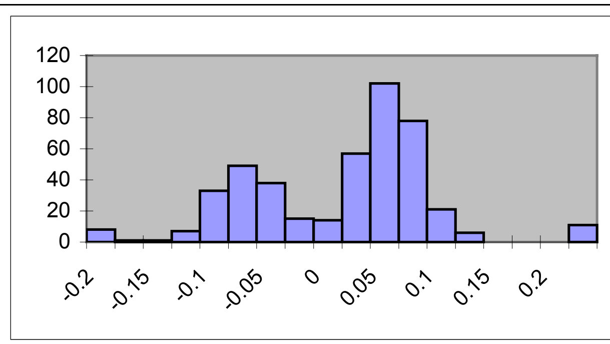
For this project, data was collected using a Leica Geosystems ALS40 (Leica 2002). The test area was a small municipal airport in Fitchburg, Massachusetts. Data was collected in the clover leaf fashion (see Calibration Errors) with 2 strips flown at 800m and a field of view of 32.3 degrees, and a third strip flown at 1600m with a field of view of 18 degrees. The data was collected with a pulse rate of 28kHz and a scan rate of 25Hz. This resulted in an overlapping area of (460 by 420 metres) which contained approx 900,000 points spaced roughly every 1 metre. The test area contained 435 known points over the runway area.

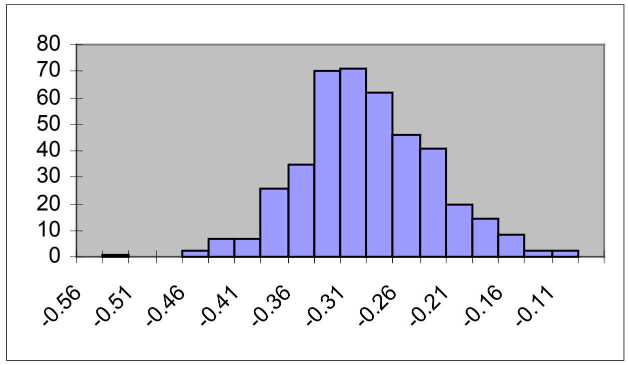
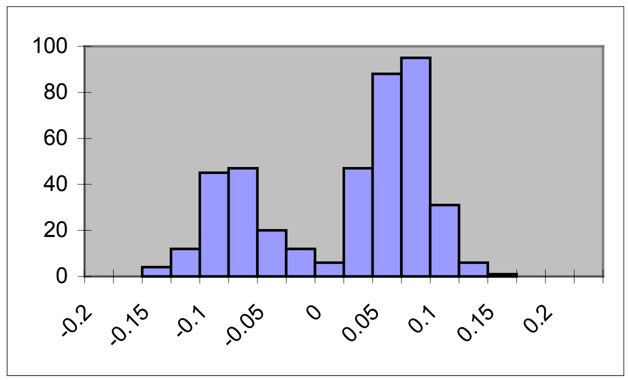
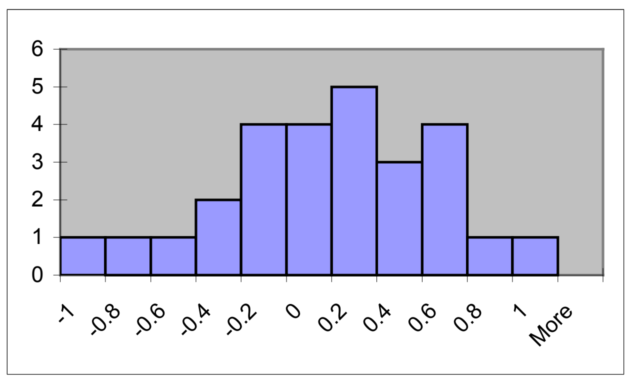
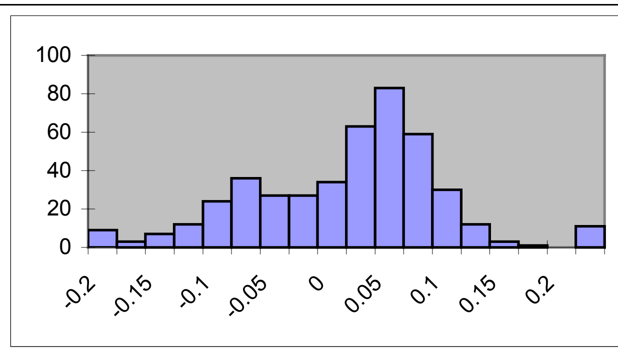
This project is proceeding on a phased basis, with the first phase intended to test the adjustment model. For this phase, tie points have been collected manually using a digital photogrammetric workstation. Although not optimal, this provided tie point data of sufficient quality to test the adjustment model. In addition to the tie points, the known points were measured in the data and used to compare the solutions with and without control.

RESULTS

The following tables summarize the adjustment results using different combinations of control points, tie points and adjustment models. The two models tested were a solution for the bore sight angles only and a 5-parameter solution that contained 2 scanner corrections. The inputs indicate what values were adjusted. The solutions are the misalignment angles determined by the adjustment. The RMS values are a comparison of the residual errors from the adjusted points to the control or average tie point values. For control points, more weighting was applied to the elevation values to compensate for the inaccuracies in manually measuring the points. The elevation residual plots help to indicate whether there is any systematic error remaining in the solution. Systematic errors are usually present when the residuals are not centered on zero or demonstrate a non-normal distribution.

In general, the results (Tables, following pages) from the bore sight only adjustment seem to show that a fairly good result can be obtained from the misalignment angles only. The adjustment with the control points gives a solution that tends to agree with the non-control point solutions. An important observation from the residual plot however is that there is still some systematic error present. This is most likely caused by unmodeled errors in the GPS/INS system and would require additional strip adjustment to remove (Morin and El-Sheimy 2001b).

Bore Sight Only Adjustment Model	
Adjustment Parameters	Elevation Residual Plot
Input: 138 Control Points weighted to favor elevation over planimetric control 3:1 **Solution (degrees):** Ω: -1.188349 Φ: 1.253530 K: -0.243868 **RMS control (m):** Z: 0.626m	
Input: 138 tie points with no control. Tie points were weighted to favor elevation 3:1. **Solution (degrees):** Ω: -1.183009 Φ: 1.248075 K: -0.239326 **RMS tie points (m):** Z: 0.155m	
Input: 9 tie points with no control. Planimetric and elevation weighted equally. **Solution (degrees):** Ω: -1.190834 Φ: 1.250547 K: -0.212592 **RMS tie points (m):** X: 0.621 Y: 0.608 Z: 0.142	
Input: 9 tie points (equal weight XYZ) 138 tie points (preferring Z) **Solution (degrees):** Ω: -1.183779 Φ: 1.248215 K: -0.232514 **RMS tie points (m):** X: 0.572 Y: 0.622 Z: 0.154	

<table>
<tr><th colspan="2">Bore sight and Scanner Correction Adjustment Model</th></tr>
<tr><th>Adjustment Parameters</th><th>Elevation Residual Plot</th></tr>
<tr><td>Input:
138 Control Points weighted to favor elevation over planimetric control 3:1
Solution (degrees):
Ω: -1.188636
Φ: 1.253459
K: -0.247049
RMS control (m):
Z: 0.622</td><td>
</td></tr>
<tr><td>Input:
138 tie points with no control. Tie points were weighted to favor elevation 3:1.
Solution (degrees):
Ω: -1.182895
Φ: 1.248108
K: -0.239492
RMS tie points (m):
Z: 0.155</td><td>
</td></tr>
<tr><td>Input:
9 tie points with no control. Planimetric and elevation weighted equally.
Solution (degrees):
Ω: -1.185449
Φ: 1.247678
K: -0.176292
RMS tie points (m):
X: 0.675 Y: 0.574 Z: 0.148</td><td>
</td></tr>
<tr><td>Input:
9 tie points (equal weight XYZ)
138 tie points (preferring Z)
Solution (degrees):
Ω: -1.183727
Φ: 1.248063
K: -0.232476
RMS tie points (m):
X: 0.580 Y: 0.612 Z: 0.155</td><td>
</td></tr>
</table>

The adjustment with 9 tie points shows that an approximate solution can still be found without a large number of observations. This can be useful for quickly determining a misalignment to be used as an approximate value in further modeling – although the small number of observations makes it difficult to judge whether the residuals are normally distributed. The remaining solutions with 138 tie points and 138 + 9 tie points both result in similar solutions and similar RMS values. The shape of the residual plot however seems to indicate that there are additional errors going unmodeled in the solution.

The adjustment with scanner corrections shows some similar trends with the bore sight only adjustment. The control point solution varies slightly from the bore sight only solution and the residual plot shows the same systematic bias. A slightly smaller RMS value however could indicate that the additional parameters are absorbing some of the error.

An important difference in these adjustments is the residual plots from the 138-point solution and the 138 + 9 solution. The 138-solution shows the same residual distribution as the bore sight only solution. The 138 + 9 however shows a much more regular distribution; suggesting that a systematic error has been successfully removed. The difference in the inputs is the quality of the planimetric observations of the additional 9 tie points. The effect on the results would indicate that higher precisions in planimetric observations are required to properly model scanner errors. Overall, it appears that the strips used in these adjustments have a relative accuracy of approximately 15 cm taken from a flying height of 800 – 1600 metres.

CONCLUSIONS

This phase of the ALS calibration project had the goal of testing new adjustment models for the sensor misalignment angles and scanner corrections. A new model was implemented that incorporated the interpolation of tie points within the least-squares adjustment. This change allowed for the modeling of scanner errors within the adjustment. Eight tests were undertaken to determine the best fitting misalignment angles. The results indicated that:

1. Errors from the navigation system remain in the solution and require additional adjustment
2. A solution can be found without the need for control points
3. A quick and moderately precise solution can be determined from only a few tie points
4. Higher accuracy planimetric tie points are required to fully model errors in the system.

The next phase of this project will involve addressing the tie point selection process. The automated selection and processing of points should help in determining and accurate and consistent model of the calibration parameters. With a good calibration, ALS systems can continue to achieve high quality results for 21st century mapping.

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