ADJUSTMENT OF LASER SCANNER DATA FOR CORRECTION OF ORIENTATION ERRORS

Helén Burman
Department of Geodesy and Photogrammetry
The Royal Institute of Technology
Stockholm, Sweden
helen@geomatics.kth.se

Working Group III/1

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ABSTRACT

GPS and INS measurements are used for georeferencing of laser scanner data. Errors in the GPS and INS measurements are propagated to the co-ordinates of the ground point reflecting the laser beam. In this paper, discrepancies between overlapping laser strips are modelled as orientation errors. The discrepancies are measured, both in elevation and in intensity data, through matching in height and plane. Special interest is put on the alignment between the INS and the laser scanner co-ordinate system. It is shown that all three alignment angles; roll, pith and heading, can be found without ground control if the same area is covered by at least three laser strips flown in different directions providing there are height or intensity gradients in the area. To get redundancy, the recommended configuration is to cover the area with four strips in four different directions. The same method used for alignment can be used for adjustment of blocks of overlapping laser strips.

1 INTRODUCTION

The LRF (Laser Range Finder) measures distances from the sensor to the reflecting target and the reflected energy (intensity). The co-ordinates of the reflecting target can be calculated if we know the laser beam orientation, which can be measured by GPS and INS. A difference between two or more laser strips covering the same area can be caused by orientation errors, which in their turn can be caused by positioning errors, misalignment between the LRF and the inertial system or by drift or bad initialisation of the inertial system. Many of these errors can be corrected for by a set of shift and/or drift parameters, see e.g. (Kilian *et al.* 1996) or (Lemmens 1997). This method is used in GPS-supported block triangulation where each strip has its own set of parameters. The same method can be used for adjusting laser strips to make them coincide in overlapping areas. Both elevation and intensity data in overlapping lasers strips are matched. The two different types of observations complement each other as they often create large gradients in different areas. A more extensive description of the work presented in this paper can be found in (Burman 2000).

2 THE OBSERVATION EQUATION

A laser scanner observation (a laser shot) is denoted $(X, Y, Z)_l$, and is obtained from the processed laser data. The co-ordinates of a laser shot is a function of the exterior orientation of the sensor (the Laser Range Finder (LRF)) and the laser shot vector. We introduce a shift in the GPS co-ordinates, $(X_d, Y_d, Z_d)^T$, to model errors in the GPS co-ordinates, *e.g.* caused by errors in the datum transformation or tropospheric delay. Assuming the GPS antenna vector is known the following equation is formulated.

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_l = \begin{pmatrix} X_0 \\ Y_0 \\ Z_0 \end{pmatrix} + \begin{pmatrix} X_d \\ Y_d \\ Z_d \end{pmatrix} + \left(\mathbf{R}_{INS} \cdot \mathbf{R}_{INS}^{LRF}\right) \cdot \begin{pmatrix} l_x \\ l_y \\ l_z \end{pmatrix}_{LRF} \tag{1}$$

$(X, Y, Z)_l^T$ *laser shot co-ordinates in the local frame*

$(X_0, Y_0, Z_0)^T$ *position of the laser scanner (GPS measured position corrected for antenna eccentricity)*

$(X_d, Y_d, Z_d)^T$	*shift of the GPS positions relative to the local frame due to errors in the datum transformation*
$\mathbf{R}_{INS}$	*rotation matrix between the inertial frame and the local frame*
$\mathbf{R}_{INS}^{LRF}$	*rotation matrix between the inertial frame and the sensor(LRF) frame*
$(l_x, l_y, l_z)_{LRF}^T$	*laser shot vector in the sensor(LRF) frame*

For simplification, the following denotations are introduced:

$$\mathbf{R} = \mathbf{R}_{INS} \cdot \mathbf{R}_{INS}^{LRF} \qquad (2)$$

$$\overline{\mathbf{R}} = \mathbf{R}_{INS} \cdot \overline{\mathbf{R}}_{INS}^{LRF}$$

Laser scanning is now regarded as a technique to model terrain surface. Assume that we want to derive a rectangular grid of elevations, which increments are labelled i and j.

$$Z_{i,j} = f_Z(X, Y) = F_Z(i, j) \qquad (3)$$

The gradient in Z in the X and Y direction is finite and exists for all Z.

$$\begin{aligned} Z_X^{'} &= \frac{\partial f_Z}{\partial X} = \frac{Z_{i+1,j} - Z_{i,j}}{X_{step}} \\ Z_Y^{'} &= \frac{\partial f_Z}{\partial Y} = \frac{Z_{i,j+1} - Z_{i,j}}{Y_{step}} \end{aligned} \qquad (4)$$

$(X, Y)_{step}$	*distances between nodes in grid*

Some laser scanner systems register the intensity of each reflected laser shot. Equivalent to elevation the intensity is continuos in at least some parts of the laser scanned area and the I (intensity value) can be expressed as function of X and Y (horizontal co-ordinates).

A laser shot, $(X,Y,Z)_{l}$, can be related to the grid through interpolation of the four surrounding nodes.

$$Z_l = (1-x)\cdot(1-y)\cdot Z_{i,j} + x\cdot(1-y)\cdot Z_{i+1,j} + (1-x)\cdot y\cdot Z_{i,j+1} + x\cdot y\cdot Z_{i+1,j+1} \qquad (5)$$

$$x = \frac{(X_l - X(i))}{X_{step}} \quad ; \quad y = \frac{(Y_l - Y(j))}{Y_{step}} \qquad (6)$$

$(X,Y,Z)_l$	*laser shot co-ordinates*
$X(i), Y(j)$	*grid co-ordinates*
x, y	*normalised position co-ordinates within the four nodes*

Equivalent interpolation can be done for intensity.

The observation equation for elevation measurements (combining equation 1 and 5) will after linearisation be:

$$
\begin{aligned}
\lambda_{Z\,l} = {} & Z_X^{`} \cdot dX_d + Z_Y^{`} \cdot dY_d - dZ_d + \\
& + \left(Z_X^{`} \frac{\partial R_X}{\partial r} + Z_Y^{`} \frac{\partial R_Y}{\partial r} - \frac{\partial R_Z}{\partial r} \right) \cdot \begin{pmatrix} l_x \\ l_y \\ l_z \end{pmatrix} \cdot dr + \\
& + \left(Z_X^{`} \frac{\partial R_X}{\partial p} + Z_Y^{`} \frac{\partial R_Y}{\partial p} - \frac{\partial R_Z}{\partial p} \right) \cdot \begin{pmatrix} l_x \\ l_y \\ l_z \end{pmatrix} \cdot dp + \\
& + \left(Z_X^{`} \frac{\partial R_X}{\partial h} + Z_Y^{`} \frac{\partial R_Y}{\partial h} - \frac{\partial R_Z}{\partial h} \right) \cdot \begin{pmatrix} l_x \\ l_y \\ l_z \end{pmatrix} \cdot dh + \\
& + (1-\overline{x}) \cdot (1-\overline{y}) \cdot dZ_{i,j} + \overline{x} \cdot (1-\overline{y}) \cdot dZ_{i+1,j} + \\
& + (1-\overline{x}) \cdot \overline{y} \cdot dZ_{i,j+1} + \overline{x} \cdot \overline{y} \cdot dZ_{i+1,j+1}
\end{aligned}
\tag{7}
$$

λ_{Z_l}	*discrepancy between measured and approximate value*
$(dX_d, dY_d, dZ_d)^T$	*updates to the unknown datum shift*
r, p, h	*roll, pitch, heading*
dr, dp, dh	*updates to the unknown misalignment angles*
$dZ_{i,j}$	*updates to the unknown elevation grid*
$\overline{x}, \overline{y}$	*approximate values of normalised co-ordinates within the four surrounding grid points*

Also differences in intensity values serve as observations and their observation equation will be:

$$
\begin{aligned}
\lambda_{I\,l} = {} & I_X^{`} \cdot dX_d + I_Y^{`} \cdot dY_d + \\
& + \left(I_X^{`} \frac{\partial R_X}{\partial r} + I_Y^{`} \frac{\partial R_Y}{\partial r} \right) \cdot \begin{pmatrix} l_x \\ l_y \\ l_z \end{pmatrix} \cdot dr + \\
& + \left(I_X^{`} \frac{\partial R_X}{\partial p} + I_Y^{`} \frac{\partial R_Y}{\partial p} \right) \cdot \begin{pmatrix} l_x \\ l_y \\ l_z \end{pmatrix} \cdot dp + \\
& + \left(I_X^{`} \frac{\partial R_X}{\partial h} + I_Y^{`} \frac{\partial R_Y}{\partial h} \right) \cdot \begin{pmatrix} l_x \\ l_y \\ l_z \end{pmatrix} \cdot dh + \\
& + (1-\overline{x}) \cdot (1-\overline{y}) \cdot dI_{i,j} + \overline{x} \cdot (1-\overline{y}) \cdot dI_{i+1,j} + \\
& + (1-\overline{x}) \cdot \overline{y} \cdot dI_{i,j+1} + \overline{x} \cdot \overline{y} \cdot dI_{i+1,j+1}
\end{aligned}
\tag{8}
$$

$dI_{i,j}$	*updates to the unknown intensity grid*

If there are ground control points available, they will be introduced as additional observations of the elevation or intensity grid.

3 THE ALIGNMENT PROBLEM

In the alignment problem, the rotation between the INS and the laser scanner co-ordinate system is to be determined. In this chapter, a number of different test configurations will be discussed in order to define an optimal alignment set-up.

Studying the observation equations one can see that there are linear dependencies between the unknowns. *E.g.* a shift along the flying direction can be explained by a positioning or by a pitch error. A shift across the flying direction can be explained by a position or by a roll error. Therefore, the datum error has to be known or be the same for the whole alignment flight. When no ground control is used, the datum errors are assumed to be zero and this is included in the adjustment by additional observations with high weights.

If there are no gradients (flat area), only the roll misalignment can be solved by measuring the differences in elevation between two strips (figure 1).

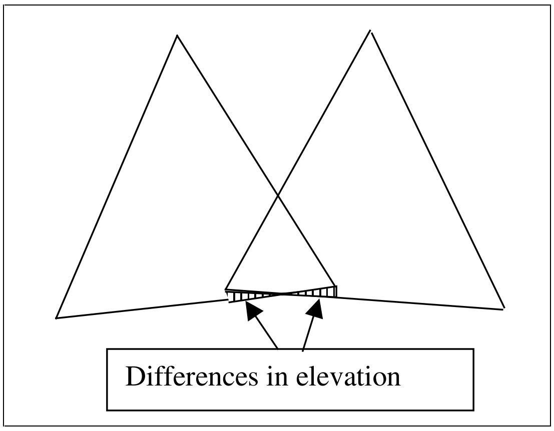

Figure 1 Misalignment in roll causes discrepancies between strip also in flat areas.

If there are ground control points, all misalignment angles can be solved but two strips have to be flown to be able to separate datum errors from misalignment, providing there are gradients in elevation or intensity.

If no ground control is used, the only observations are differences between the strips. As mentioned before, the datum errors are then assumed to be zero. Two strips flown in different directions will cause linear dependencies between the three angles (figure 2).

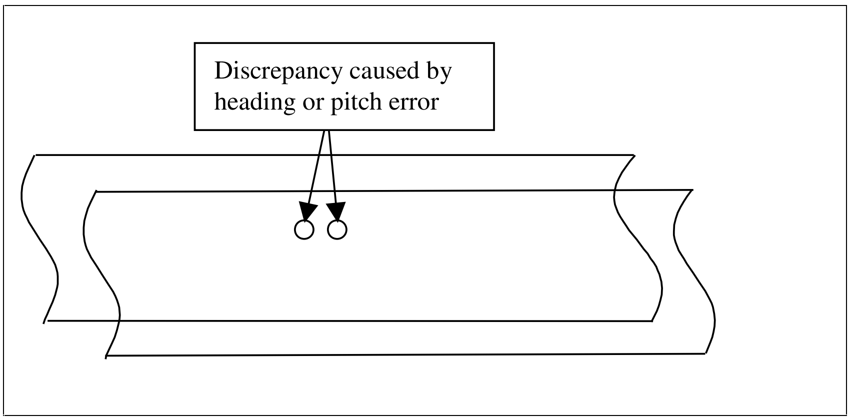

Figure 2 Example of linear dependency between misalignment angles.

To solve for all misalignment angles only by measuring differences between strips, at least three strips flown in different directions are needed.

3.1 Recommendations

To get redundancy in the measurements, it is advised to have four strips crossing each other and to measure elevation or intensity differences at the borders of the strips (figure 3).

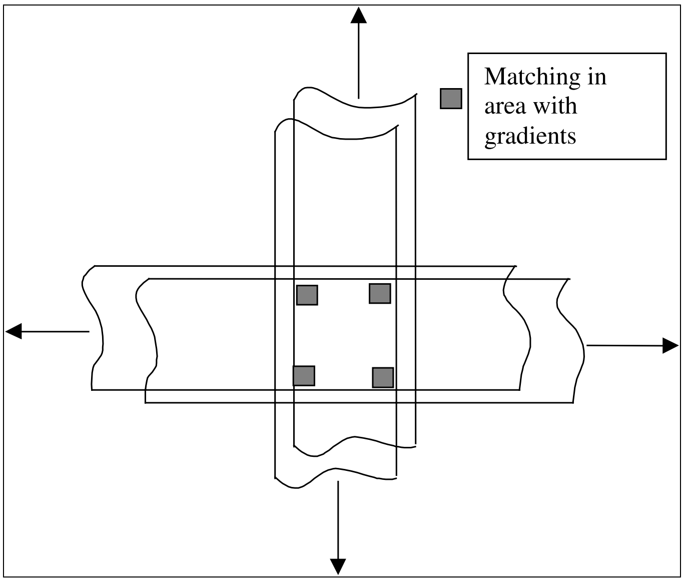

Figure 3 Recommended configuration for the alignment procedure.

4 MATCHING PROCEDURE

Interest points to be used for matching are chosen by searching for points with large gradients, either in one or both (X and Y) directions. This is to find points, corners or edges. For this, approximate values one grid of height and one grid of intensity values are calculated from the irregular laser data by using the finite element method. Large gradients are found by using the Sobel filter. Within a 7x7 window, the square sum of the gradients in X and Y are calculated and the final weight is calculated as the Root Square of these values.

$$w = \sqrt{\sum_{j=1}^{7}\sum_{i=1}^{7}\left(q_{X\,i\,j}\right)^2 + \sum_{j=1}^{7}\sum_{i=1}^{7}\left(q_{Y\,i\,j}\right)^2} \qquad (9)$$

w *weight of interest*
$q_{Xi,j}$ *grid point (i,j) Sobel-filtered in X-direction*
$q_{Yi,j}$ *grid point (i,j) Sobel-filtered in Y-direction*

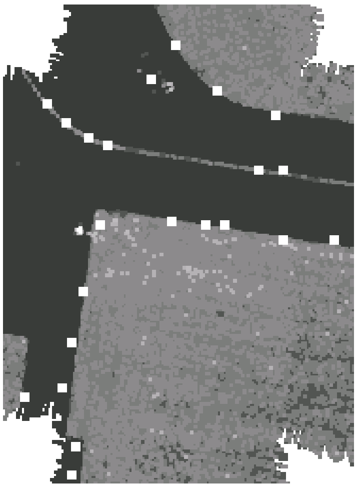

Figure 4 Example of interest points in an intensity image.

A dense grid of 21x21 pixels with about the same resolution as the laser data, was defined around each interest point. Approximate values were then again calculated using the finite element method and using all laser measurements within the area of interest. Gradients were calculated by using the Sobel filter. Each laser measurement within the interest area produces one observation equation (equation 7 or 8). All observations from all areas of interest were put into one least-squares adjustment and the unknown orientation errors were solved. As the observation equations are linearised, the process was repeated until convergence. To avoid forested areas (which produce high gradients), a criteria was put on the matching areas that a majority of the grid points should be describing a flat surface. This was done through Laplace-filtering of the interest area.

5 PRACTICAL TESTS

Test area 1: A runway with flat and open terrain with large intensity differences between grass and hard-made surfaces and high reflecting painted lines. The area was covered four times from 60 meters height in four directions (east-west, west-east, north-south and south-north).

Test area 2: An oblong building and small undulations in the rest of the area. Large intensity differences between grass and hard-made surfaces. There is both open and forested terrain. Two strips flown at 60 meters height in two opposite directions (east west and west east).

The matching grid was chosen to approximately correspond to the resolution of laser points on ground. For 60 metres flying height, the grid had a resolution of 0.2 meter.

5.1 Result

Table 1 Result from matching test area 1.

Type of observation	Mean discrepancy in elevation after adjustment [mm]	droll [mrad]	dpitch [mrad]	dheading [mrad]
Intensity-gradient	--	1.65 +/- 0.04	-2.74 +/- 0.04	0.98 +/- 0.25
Height-gradient	--	--	--	--
Height-difference	Strip 1: 5.7 Strip 2: -4.9 Strip 3: -4.6 Strip 4: 0.9	2.02 +/- 0.01	--	--
All	Strip 1: 7.1 Strip 2: -6.0 Strip 3: -5.1 Strip 4: 0.4	1.96 +/- 0.01	-2.72 +/- 0.03	-0.77 +/- 0.19

Figure 5 Test area 1, intensity data.

The heading solution after matching only intensities than after matching all data. This difference is though very small (less than 15 millimetres on ground). The difference between solutions differs less than 1/10 of a pixel (0.20/10 = 0.02 meter).

Table 2 Result from matching test area 2.

Type of observation	Mean discrepancy in elevation after adjustment [mm]	droll [mrad]	dpitch [mrad]	dheading [mrad]
Intensity-gradient	--	4.05 +/- 0.13	-6.00 +/- 0.11	--
Height-gradient	--	--	--	--
Height-difference	Strip 1: 1.5 Strip 2: -3.2	5.18 +/- 0.02	--	--
All	Strip 1: 1.5 Strip 2: -3.2	4.34 +/- 0.01	-5.13 +/- 0.03	--

Figure 6 Test area 2, elevation data.

The worst discrepancy between solutions is about 1/3 pixel (0.20/3 = 0.067 meter). Profiles of the building before and after correction for orientation errors are visualised in figure 6.

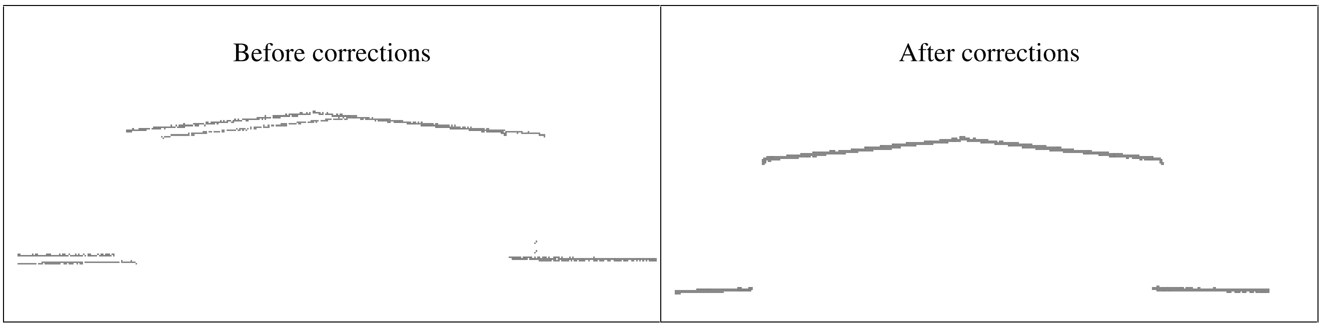

Figure 7 Profiles of the building in test area 2 (two laser strips in opposite directions) before and after correction of orientation errors.

6 SUMMARY AND CONCLUSIONS

The two main reasons for developing the laser strip adjustment are alignment calibration and block adjustment to make overlapping strips coincide in one surface. Three groups of observation equations are used in a least-squares adjustment in order to make overlapping laser strips coincide. Two of them are based on finding features for matching elevation or intensity values in plane and one is for finding corresponding surfaces for matching in height. Problems in forested areas can be overcome by filtering vegetation from the laser data. The remaining ground surface can then be used for matching.

In the alignment procedure, the main interest is to estimate the misalignment angles between the sensors. These angles are the same for the whole flight. Therefore, one set of attitude shift parameters can be used for the whole block. The estimates of shift parameters for the position are strongly correlated with the attitude errors. The estimate of the pitch error is correlated with a shift along the flying direction and the roll error is correlated with a shift across the flying direction. The position shifts has to be known or be the same for all strips if the misalignment is to be determined.

Misalignment in roll and pitch can be found from differences between two strips flown in opposite directions while at least three strips in different directions are needed to solve all three misalignment angles. To get redundancy, the recommended configuration for alignment is to cover the area from four different directions. The gradient matching method assumes a continuos surface with only one elevation or intensity value for each pair of (X,Y) co-ordinates. In this investigation, intensity gradients (*e.g.* between hardmade surfaces and grass) suited best for this. The reason for this is probably that these occurred at flat surfaces not geometrically sensitive for scanning direction. Large gradients in height are often found in buildings. They are not suited for matching as the roof reaches over the wall, which not follows the criteria of a continuos surface. In addition to this, large height differences often produce shadows, disturbing the surface reconstruction.

When the reference height grid is unknown, it is estimated before each iteration by calculating the mean height value of all laser strips. The laser strips are corrected for orientation errors, which are updated from the last iteration.

As for alignment calibration, the method can be used for adjustment of larger blocks of overlapping laser strips. If the accuracy in georeferencing does not match the precision of the laser scanning, there might be effects like multiple layers in overlapping areas. This can be annoying in visualisation of the result and in visual or automatic interpretation techniques. Some additional features should be added to the automatic matching procedure for adjustment of laser data. One is modelling the intensity difference in one object between different laser strips. Another is including feature extraction to match edges. A third is including the option of having the height model as an unknown in the adjustment. Finally, some self-diagnosis should be included to assign weights for the observations. In the present version, weights are based on the à priori variances of the observations. In this example, only shift of the attitudes and positions are used. The method can be expanded to also model time dependent drift in the orientation parameters.

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