LASER STRIP ADJUSTMENT FOR DATA CALIBRATION AND VERIFICATION

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Commission VI, WG VI/4

KEY WORDS: Laser strips, Least-Squares, Adjustment, Matching, GPS, INS

ABSTRACT:

Laser scanning is dependent on georeferencing by satellite positioning and inertial navigation to give orientation of each laser shot. Orientation errors are at the same time one of the main contributors to the laser data error budget. Satellite positioning error like atmospheric delay, cycle slips and loss-of-lock together with drifts in accelerometers and gyros in the inertial system results in orientation errors which often are of a systematic nature. Some errors can be corrected for by making overlapping laser strips coincide and by making laser strips coincide with ground truth. In this purpose a laser strip adjustment program, TerraMatch, was developed. This paper presents the mathematical model used, the main features of the program and results from practical tests.

1. INTRODUCTION

1.1 Airborne laser scanning

This paper deals with airborne laser scanning. The main configuration of such a system is a laser range finder that operates with a scanning devise. There is one GPS receiver in the rover (helicopter or airplane) and at least one reference receiver on ground for relative positioning. Rotation movements are measured by an inertial measuring unit (IMU), which is rigidly attached to the same frame as the laser scanner.

Although the resulting accuracy of the reflected laser point has several error sources, this paper concentrates on orientation errors. These errors are often systematic and can therefore be modelled in an adjustment procedure. Laser strip adjustment has been proposed by e.g. (Burman 2000a), (Crombaghs et al. 2000) and (Maas 2000) as a tool for modelling and correct for orientation errors.

1.2 Error sources

There are different errors in laser scanning, which are of different nature, e.g.

- Object does not reflect the laser beam
- Erroneous laser length
- Erroneous orientation of laser vector

These errors have numerous different causes. Some *materials* absorb the light and some, like water, does not scatter the laser beam but reflects it away in another direction.

Different materials give *different reflectance signature*. Some of this is compensated for when the laser range finder is calibrated at a test range with different ranges and materials. The result is often hard coded in the laser range finder.

There are different types of *scanning devises* but they all have to measure their internal movements, e.g. mirror angle. Any error in the measured movement will give an erroneous orientation of laser beam.

The laser *"footprint"* is not a point but an area, which will affect the intensity and signature of the reflected signal. The *"footprint"* might cover different material and different heights, e.g. trees, bushes, grass, asphalt or buildings. A laser beam hitting a slanted surface can cause errors in length. This effect is visible when the laser beam is close to parallel to the surface.

Positioning of the laser is mainly done by GPS, *i.e. satellite positioning*. This can be afflicted by errors like atmospheric delay, erroneous ambiguity resolution, cycle slips, multipath and loss-of-lock. Positioning errors are directly transferred to the ground coordinates of the reflecting laser point.

The rotations are measured by an inertial system, which consists of three accelerometers in three orthogonal axes and three gyros that measures rotational rates around these axes. Both *accelerometers and gyros* are afflicted by time dependent drift. This causes errors in rotation angles.

This paper describes a method to model and correct for shift and linear drift of orientation positions and attitudes.

2. MATHEMATICAL MODEL

A measured laser length, ***l***, can be related to ground coordinates by knowing the position and direction of the laser beam.

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_G = \begin{pmatrix} X_0 \\ Y_0 \\ Z_0 \end{pmatrix} + R_{IMU} R_{IMU}^{LRF} R_M \begin{pmatrix} 0 \\ 0 \\ l \end{pmatrix} \qquad (1)$$

where $(X, Y, Z)_G$ = coordinates of point on ground
(X_0, Y_0, Z_0) = position of the laser scanner (GPS measured position corrected for antenna eccentricity)
$\mathbf{R}_{INS}$ = IMU rotation matrix (body to ground frame)
$\mathbf{R}_{INS}^{LRF}$ = misalignment between laser and IMU
R_M = rotation matrix of laser mirror (scanning angle)
l = laser length

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 TIN surface of elevations.

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

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

$$Z_X^{'} = \frac{\partial f_Z}{\partial X}$$

$$Z_Y^{'} = \frac{\partial f_Z}{\partial Y}$$

(4)

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). The gradient in a point (X, Y) can be found in the normal vector of the triangle plane (figure 1).

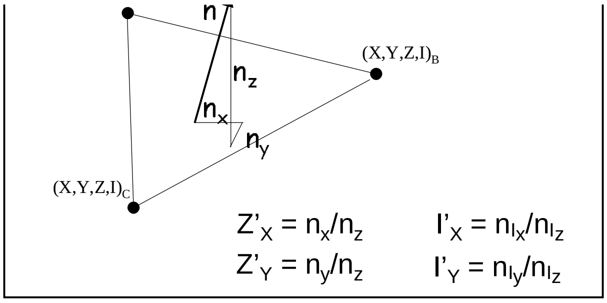

Figure 1. Gradients can be derived from the TIN surface.

A laser shot, $(X,Y,Z)_l$, can be related to the TIN surface through interpolation of the three surrounding nodes. In this way, original laser point can be used avoiding error contribution from regular grid interpolation (Maas 2000)..

Equivalent interpolation can be done for intensity.

The observation equation for elevation measurements (combining equation 1 and 4) will after linearisation be:

$$\begin{aligned}\lambda_{Z\,l} &= Z_X^{'} \cdot dX_0 + Z_Y^{'} \cdot dY_0 - dZ_0 + \\ &+ \left(Z_X^{'} \frac{\partial R_X}{\partial r} + Z_Y^{'} \frac{\partial R_Y}{\partial r} - \frac{\partial R_Z}{\partial r} \right) \cdot \begin{pmatrix} l_x \\ l_y \\ l_z \end{pmatrix} \cdot dr + \\ &+ \left(Z_X^{'} \frac{\partial R_X}{\partial p} + Z_Y^{'} \frac{\partial R_Y}{\partial p} - \frac{\partial R_Z}{\partial p} \right) \cdot \begin{pmatrix} l_x \\ l_y \\ l_z \end{pmatrix} \cdot dp + \\ &+ \left(Z_X^{'} \frac{\partial R_X}{\partial h} + Z_Y^{'} \frac{\partial R_Y}{\partial h} - \frac{\partial R_Z}{\partial h} \right) \cdot \begin{pmatrix} l_x \\ l_y \\ l_z \end{pmatrix} \cdot dh\end{aligned} \qquad (5)$$

where λ_{Z_l} = discrepancy between measured and approximate value

$(dX_0, dY_0, dZ_0)^T$ = updates to the unknown datum shift

(r, p, h) = roll, pitch, heading

(dr, dp, dh) = updates to the unknown misalignment angles

Also differences in intensity values serve as observations (Maas 2001) and their observation equation will be:

$$\begin{aligned}\lambda_{I\,l} &= I_X^{'} \cdot dX_0 + I_Y^{'} \cdot dY_0 + \\ &+ \left(I_X^{'} \frac{\partial R_X}{\partial r} + I_Y^{'} \frac{\partial R_Y}{\partial r} \right) \cdot \begin{pmatrix} l_x \\ l_y \\ l_z \end{pmatrix} \cdot dr + \\ &+ \left(I_X^{'} \frac{\partial R_X}{\partial p} + I_Y^{'} \frac{\partial R_Y}{\partial p} \right) \cdot \begin{pmatrix} l_x \\ l_y \\ l_z \end{pmatrix} \cdot dp + \\ &+ \left(I_X^{'} \frac{\partial R_X}{\partial h} + I_Y^{'} \frac{\partial R_Y}{\partial h} \right) \cdot \begin{pmatrix} l_x \\ l_y \\ l_z \end{pmatrix} \cdot dh\end{aligned} \qquad (6)$$

Further information about the underlying theory can be found in (Burman 2000b).

2.1 TerrMatch features

The main procedure using TerraMatch is

1. Data preparation
2. Matching strips and applying corrections
3. Output of matching report

Data preparation includes managing trajectories and filtering laser data. The data needed for matching is

- Trajecory data with time stamps, i.e. (time, X, Y, Z, roll, pitch, heading) for each flightline
- Laser data with time stamps (time, X, Y, Z, (I), flightline number)
- Ground control points (X,Y,Z) (optional)

Trajectory data is needed so that the laser data can be oriented, which is done by comparing time stamps. Trajectories are numbered and equivalent numbering is used for the laser data. As the matching procedure depends on continuous surfaces, laser data has to be filtred so that continuous surfaces belong to one class. One continuous surface is ground and another can be roof. In the TerraScan software, there are possibilities to make classification of ground and buildings (Axelsson, 2000), see figure 2.

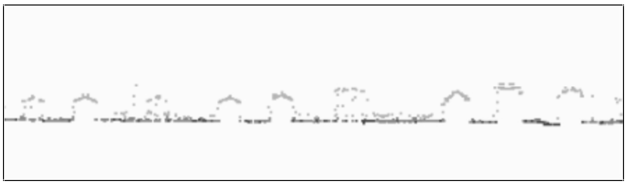

Figure 2. Classified ground in TerraScan

Ground control points can be used. The number and character of points deside how they can be used. They have to form an undulated surface if corrections in planimetry are to be made. Single sparse points can only be used for shifting laser data up or down.

In the matching procedure there are a number of settings to be made.

1. À priori standard deviation of unknowns (shift and drift parameters)
2. Convergence criteria
3. Choosing point class to be matched
4. Choosing unknowns to be solved

One has to choose how dense the observations (measured elevation differense) should be made, from every laser point to every 1000nd.

The unknowns can be

- Shift and/or drift in Easting
- Shift and/or drift in Northing
- Shift and/or drift in Height
- Shift and/or drift in roll
- Shift and/or drift in pitch
- Shift and/or drift in heading

There is also an option wether to make the same correction for the whole data set or make the correction for individual strips. When calibrating misalignment between laser scanner and INS, corrections for the whole data set is typically used.

One option is to also use intensity measurements but in the writing moment it has not been tested.

The output report has information about number of laser points, number of observations, standard error of unit weight and elapsed time in the matching procedure.

3. PRACTICAL TESTS

This is a presentation of some of the results from practical tests. Two calibration projects were flown to calibrate misalignment between laser scanner and IMU. The Gävle project was mainly done to investigate if laser scanning can be used for updating the national height database of Sweden. The rest of the projects were made for production of detailed DEM.

	Flying height [m]	No of strips	No of points	Operator
Calibration 1	100	4	312 089	TopEye
Calibration 2	100	4	562 166	TopEye
Svinesund	700	6	4 000 000	Fotonor
Toensberg	600	9	4 000 000	Fotonor
Gävle	1 700	5	3 800 000	Fotonor

Table 1. List of practical test sights

3.1 Calibration flight 1

In the calibration flight made by TopEye, the purpose was to establish the roll and pitch offset between the laser scanner and the IMU. These missions were flown in a four leaf pattern over an area with distinct feature on ground. In the first case the feature was a broad bank (figure 3).

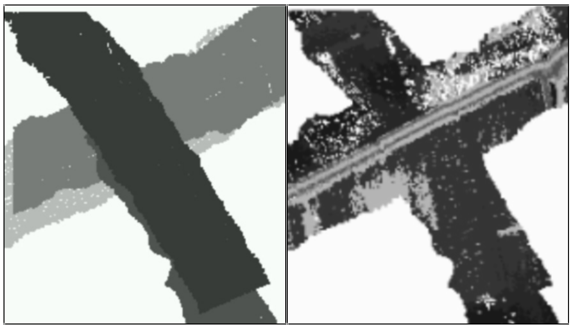

Figure 3. System calibration flight 1, four strips flown for misalignment calibration. Left: strips. Right: elevation.

In this case the laser data was filtered to get ground points. These ground points were then thinned where the change in gradient is small to get so called “ model keypoints”. These model key points were matched to get misalignment between laser scanner and IMU.

Figure 4 shows a profile of the bank before and after the calibration.

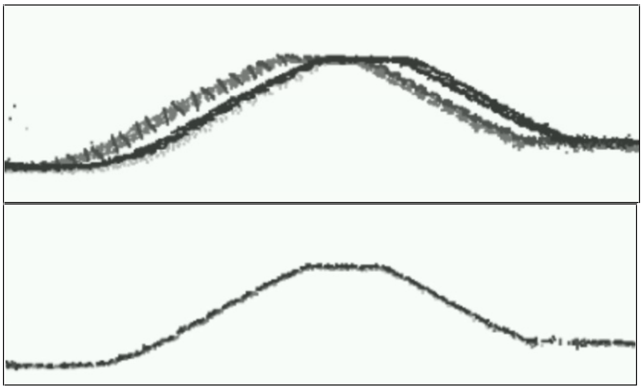

Figure 4. Profile of the calibration dataset, Above: before calibration. Below: after calibration

The final corrections for the calibration project was are presented in table 2.

Correction	[degrees]
R shift	+0.4028
P shift	-0.3625

Table 2. List of result in calibration 1

3.2 Calibration flight 2

In the other case, the features were large buildings with large roof structures (figure 5).

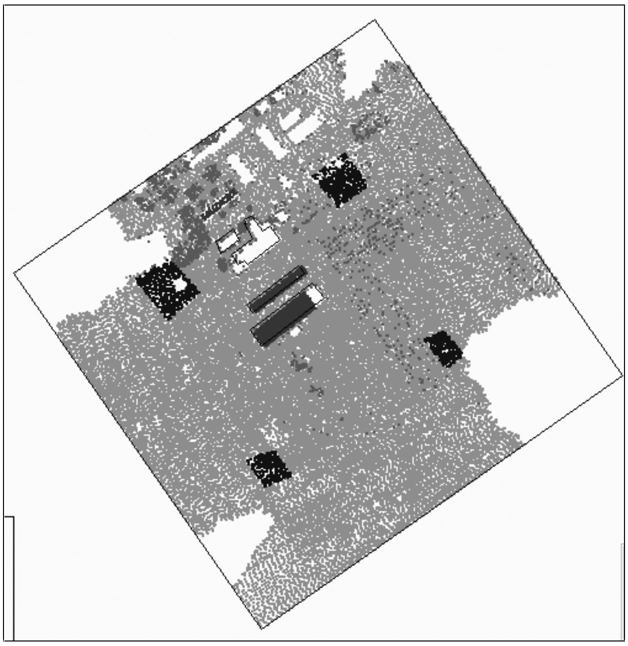

Figure 5. System calibration flight 2, four strips flown for misalignment calibration. Dark areas (flat surface and roof structures) were used for matching.

In this case, the ground was very flat so the roofs of the large buildings were used for matching together with four smaller areas with flat terrain in the corners of the overlapping area (dark areas in figure 5).

In this case it was a question of recalibration, so that the starting values were very good and the corrections were very small. This also leads to a faster process. The final corrections are listed in table 3.

Correction	[degrees]
R shift	-0.0021
P shift	+0.0113

Table 3. List of result in calibration 2

3.3 Project Toensberg

The Toensberg project was flown in nine parallel strips (figure 6). As there is no crossing strip, there was no attempt of solving for pitch or heading errors. Only elevation and roll shift were solved for.

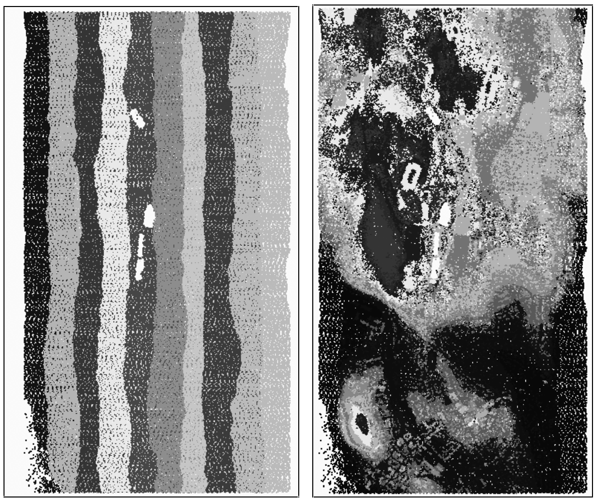

Figure 6. The Toensberg project consists of nine parallel strips (left) and moderate terrain undulation (right).

The final corrections for the Toensberg test are listed in table 4.

Flightline	Points	Z shift [m]	R shift [deg]
1	1463	-0.090	+0.0589
2	2385	-0.089	+0.0160
3	2360	-0.020	+0.0259
4	2192	-0.051	+0.0269
5	2601	-0.028	+0.0194
6	2870	-0.024	+0.0214
7	3006	-0.046	+0.0377
8	2992	-0.018	+0.0250
9	1486	-0.050	-0.0028

Table 4. List of result in project Toensberg

3.4 Project Svinesund

This laser strip adjustment was made for Fotonor to calibrate the dataset and to verify the accuracy. The terrain was very undulated and the elongated area was covered by five parallel strips and one strip across in the middle, figure 7.

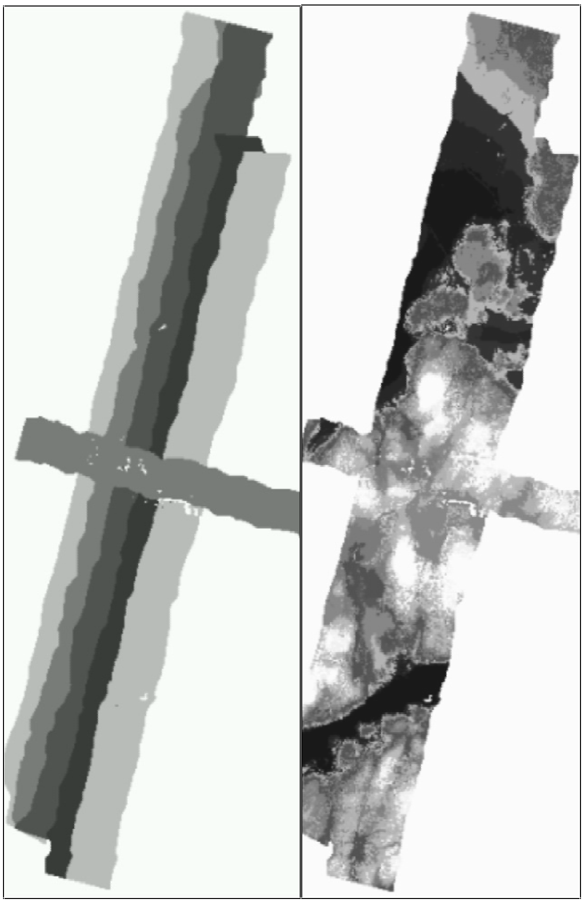

Figure 7. Project Svinesund, six strips. Left: strips. Right: elevation

In this case the crossing strip helped to discover a deformation of the strip. It is not clear what has caused the deformation but the guess is a scale factor error in the mirror roll angle. The same kind of deformation was found by (Crombaghs et al. 2000). This deformation was not modelled or compensated for.

The final corrections for the project Svinesund are presented in table 5.

Flightline	Points	Z shift [m]	H shift [rad]	R shift [rad]	P shift [rad]
1	778	-0.010	-0.0005	-0.0001	+0.0001
5	626	+0.027	-0.0004	-0.0001	-0.0000
2	1188	-0.028	-0.0008	-0.0003	+0.0001
4	1070	-0.001	-0.0000	-0.0001	+0.0000
3	1180	-0.023	-0.0003	-0.0001	+0.0002
6	777	+0.009	-0.0001	-0.0000	+0.0003

Table 5. List of final corrections in the Svinesund project.

3.5 Project Gävle

Fotonor flew this mission for the National Land Survey of Sweden. The main purpose was to investigate the possibilities of using laser scanning to update the National Height Data Base in Sweden. Therefore, the flying altitude was rather high (about 1700 m). They wanted cover different land use categories, which lead to a rather elongated flight with five different strips (figure 8). The area was rather flat (figure 9) and most of it was covered by forest.

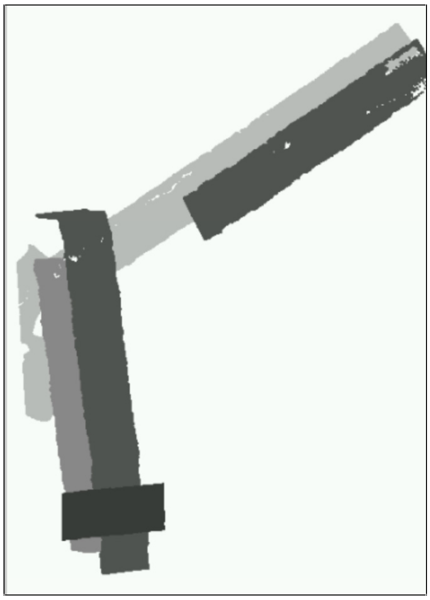

Figure 8. Strips in the Gävle project

Figure 9. Elevation in the Gävle project

The final corrections are listed in table 6.

Flightline	Points	Z shift [m]	R shift [deg]
5	816	-0.120	-0.0192
4	1784	-0.029	-0.0004
3	2212	+0.015	+0.0099
2	2033	-0.178	-0.0026
1	3278	+0.137	+0.0017

Table 6. List of final corrections in the Gävle project.

In this case there was an elevation offset between the two strips in the north. This can be illustrated by thinning the ground points where there is a small change in gradient, i.e.

finding the "model keypoints". If there is a large elevation difference in elevation, which is the case with discrepancy between two strips, more points are needed. Figure 10 shows the effect on model keypoints before and after laser strip adjustment.

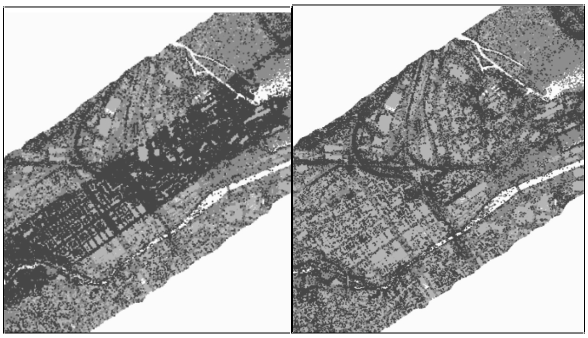

Figure 10. "Model keypoints" in the Gävle project. In the left image are model key points before and in the right after the strip adjustment.

3.6 Summary of results

A summary of the results is presented in table 7. As one can see, the standard error of unit weight presents

	s_0 [m]	Observation density [n:th point]	Time [s]	No of obs.
Calibration 1	0.0465	5	1033.6	5 000
Calibration 2	0.0350	1	56.4	19 000
Svinesund	0.0992	100	2335.5	5 600
Toensberg	0.1093	100	563.4	20 000
Gävle	0.0960	200	409.0	10 000

Table 7. List of result in practical test sights

The strip adjustment method used in this case depends on measured elevation differences between strips and difference towards known points. There are often many observations and a few unknowns. In most cases this is a favourable situation but in this case it can cause slow convergence. Assume there is an area of flat terrain with a couple of ditches. Planimetric discrepancies between laser strips will only cause discrepancy in the position of the ditch. Assume that you make observations in all laser points, most of them will show no elevation difference while just a few, e.g. 1-5 % will show elevation discrepancies. This means that you only wish to make observations where you have discrepancies, i.e. in the areas with undulated terrain. Elevation and roll errors are on the other hand easier to solve for if the observations are spread evenly over the terrain.

4. SUMMARY AND CONCLUSIONS

Orientation errors cause systematic errors that in some cases can be modelled and corrected for in strip adjustment. There is however often a strong correlation between unknowns, which limits the possibility to compensate for all errors in all cases. In the tests presented in this paper, elevation differences and roll offsets were easiest to solve for, as they only need elevation difference measurements. Planimetry (X and Y), pitch and heading are dependent on gradients in different directions, i.e. undulated terrain. In addition to this, unknowns are strongly correlated and needs certain fly pattern and/or control information to be solved.

Issues of future improvement in the laser strip adjustment procedure can be derived from the practical tests:

- The procedure of selecting areas of interest for matching should be improved – this will speed up the convergence
- Further investigation of how to solve for different orientation unknowns should be made – this will increase the reliability of the method
- The error model should be extended to include modelling of strip deformation (might be roll mirror scale factor) – this can improve the result in many cases
- More effort should be put to matching laser reflectance intensity – this will add information in flat areas and make it possible to use e.g. painted crossroads as ground control

In all practical tests presented here there was an improvement of the result by doing a strip adjustment. There are still investigations to be made for further development of laser strip adjustment. The method is necessary for laser data calibration and accuracy verification.

5. ACKNOWLEDGEMENTS

Many thanks to TopEye AB, Fotonor AS and Terrasolid OY for their cooperation, without their help there would not be any paper. Thanks also to the National Land Survey for letting us take part of their test.

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