

CALIBRATION OF A RIEGL LMS-Z420i BASED ON A MULTI-STATION ADJUSTMENT AND A GEOMETRIC MODEL WITH ADDITIONAL PARAMETERS

D. Schneider

Technische Universität Dresden, Institute of Photogrammetry and Remote Sensing, 01062 Dresden, Germany – danilo.schneider@tu-dresden.de

Commission V, WG V/3

KEY WORDS: Terrestrial laser scanner, Geometric model, Calibration

ABSTRACT:

The paper presents the calibration and analysis of a terrestrial laser scanner Riegl LMS-Z420i. Two different calibration fields were scanned with this laser scanner from different positions. The calibration fields are equipped with signalized targets to be measured within the laser scanner point cloud interactively or automatically. The measured spherical coordinates (distance, horizontal angle and vertical angle) were used as observations in a multi-station adjustment, equivalent to a photogrammetric bundle adjustment.

In extension to the basic geometric model a set of additional parameters was used, which were determined in a self-calibration procedure. These additional parameters are partly derived from well-known error sources of geodetic instruments as axes errors or axes eccentricities and partly taken from the literature, where the calibration of other laser scanners is already described. The calibration results (parameter values, standard deviations, significance), which were calculated from the observations of both calibration fields are analyzed and compared.

The combination of the adjustment procedure with variance component estimation allows for the separate assessment of the precision of the different types observations (distance, horizontal angle, vertical angle). Thus, the precision improvement of the adjusted observations as result of a stepwise addition of calibration parameters is investigated. As object point coordinates were handled as unknowns within the adjustment, their standard deviations were calculated and analyzed. It could be shown that the use of additional calibration parameters has the potential to increase the object point precision.

1. INTRODUCTION

In many terrestrial laser scanner applications the precision of the measurements plays an important role. Examples are the use of terrestrial laser scanners for deformation analysis presented by Lindenbergh, et. al. (2005) and Schneider (2006). In order to achieve maximal precision a thorough calibration of the measurement device is required.

In most cases laser scanner manufactures calibrate their products before delivery or they offer re-calibration in regular intervals. The calibration results are directly inserted in the scanning device. The user has no access to the values and the calibration models are unknown. Subsequently, the observations (distance, angles) are corrected within the instrument automatically.

On the other hand there are well-established calibration methods for geodetic devices such as theodolites or total stations, which allow the user for a re-calibration of the instrument. Typical instrument errors such as axes errors are determined separately and afterwards calibrated or corrected as shown in Deumlich & Staiger (2002).

In comparison to the calibration procedures of geodetic instruments the calibration of cameras in photogrammetric applications bases on a mathematical defined geometric model. This model is extended by additional parameters which allow for a compensation of systematic deviations from the basic geometric model.

The photogrammetric calibration approach can be easily adapted to terrestrial laser scanners as done for example in Lichti & Franke (2005). The basic model is defined by

transformation equations between Cartesian and spherical coordinates. There are three observation equations: distance, horizontal angle and vertical angle as function of the exterior orientation (translation and rotation) of the instrument in a global coordinate system. The observation equations can be extended by correction terms to compensate for systematic distance errors such as additive correction and scale as well as angle errors such as collimation and trunnion axis error. Ideally, the correction terms contain parameters, whose values represent directly the magnitude of the appropriate instrument error. However, as the parameters are correlated among one another the interpretation of the parameter values as magnitude of the physical error is limited.

The calibration based on a geometric model with additional parameters can be considered as suitable method for terrestrial laser scanners, as these instruments are fully automatic systems where the calibration values can be applied directly. Moreover, this allows for the application of different calibration strategies. One strategy is the calibration using a test field with signalised points, whose coordinates are already known (control points). If only one laser scanner position is used, this corresponds to a space resection. The accuracy potential of the calibration method can be optimal exploited if more than one laser scanner position is used and the coordinates of object points are handled as unknown parameters. This is equivalent to a photogrammetric bundle adjustment with self-calibration. This strategy also allows for an “on-the-job calibration”, as the object, which has to be recorded, serves as calibration field at the same time. This might be advantageous in practise, and delivers best accuracies.

Other calibration methods for terrestrial laser scanners are documented in Rietdorf (2005), who suggests a calibration based on planar object features and stepwise transformations in quaternion notation. Neitzel (2006) presents a calibration procedure for the determination of the trunnion and collimation axis error of terrestrial laser scanners based on measurements from both positions of the telescope. However, this is only possible for laser scanners, which allow for measurements from both telescope positions. These are mainly panorama-view-scanners with an elliptical mirror. Amiri Parian & Grün (2005) suggest the laser scanner calibration based on the laser scanner's intensity image in combination with a geometric model equivalent to full-spherical panoramic cameras.

However, users of terrestrial laser scanners desire for reliable, comprehensible and open calibration models.

In this paper the calibration method published in Lichti (2007) – based on a multi-station adjustment and a geometric model with additional parameters – is applied to a Riegl-LMS Z420i (Riegl, 2007). For this purpose a software was developed which features the multi-station adjustment with self-calibration and variance component estimation. The software is able to process laser scanner observations in combination with image data (central perspective, panoramic, fisheye) and was already published in Schneider & Maas (2007) and Schneider & Schwalbe (2008).

Two different calibration rooms were recorded with the Riegl laser scanner. Two further parameters (axes eccentricities) were added to the geometric model proposed by Lichti (2007). The additional parameters are investigated for significance. Finally, some conclusions about the benefit of laser scanner calibration in general are drawn.

2. GEOMETRIC MODEL

2.1 Geometric model

Original observations of terrestrial laser scanners are spherical coordinates, i.e. distance D , horizontal angle α and vertical angle β . Therefore the basic geometric model of terrestrial laser scanners can be described by the definition of a spherical coordinate system (Fig. 1).

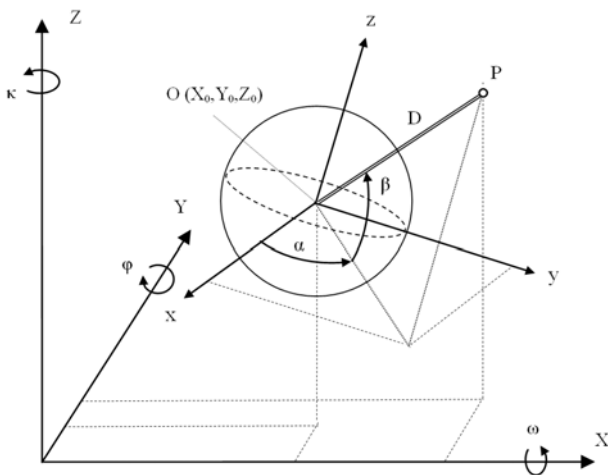


Figure 1. Basic geometric model of terrestrial laser scanners

The model equations can be written as transformation between Cartesian and spherical coordinates. In case there are physical

deviations from the basic geometric model existent, the observations can be corrected by correction terms ΔD , $\Delta\alpha$ and $\Delta\beta$ (section 2.2 and 2.3).

$$\begin{aligned} D &= \sqrt{x^2 + y^2 + z^2}, & D_{corr} &= D + \Delta D \\ \alpha &= \arctan\left(\frac{y}{x}\right), & \alpha_{corr} &= \alpha + \Delta\alpha \\ \beta &= \arctan\left(\frac{z}{\sqrt{x^2 + y^2}}\right), & \beta_{corr} &= \beta + \Delta\beta \end{aligned} \quad (1)$$

where D, α, β = distance, horizontal angle, vertical angle
 $\Delta D, \Delta\alpha, \Delta\beta$ = correction terms for observations
 x, y, z = local scanner coordinates of an object point

The local laser scanner coordinates x, y, z have to be substituted by the following equations in order express the original laser scanner observations as function of the position and orientation of the laser scanner in a global coordinate system:

$$\begin{aligned} x &= r_{11}(X - X_0) + r_{21}(Y - Y_0) + r_{31}(Z - Z_0) \\ y &= r_{12}(X - X_0) + r_{22}(Y - Y_0) + r_{32}(Z - Z_0) \\ z &= r_{13}(X - X_0) + r_{23}(Y - Y_0) + r_{33}(Z - Z_0) \end{aligned} \quad (2)$$

where X, Y, Z = object coordinates of an arbitrary point
 X_0, Y_0, Z_0 = coordinates of laser scanner position
 r_{ij} = elements of rotation matrix as function of the rotation angles (ω, ϕ, κ) between local laser scanner coordinate system and global coordinate system

Using this basic model in a space resection or multi-adjustment mode allows for the determination of the exterior orientation of one or more laser scanner positions.

2.2 Additional parameters: distance

In order to develop additional distance parameters for the compensation of systematic deviations from the basic model one has to differentiate between time-of-flight (e.g. Reshetyuk (2006)) and amplitude-modulated-continuous-wave (AM-CW) laser scanner systems. For time-of-flight systems it is sufficient to apply an additive correction to compensate for a difference between the electronic and mechanic zero point and a scale parameter to compensate for deviations caused by a deviant modulation frequency (e.g. due to aging or temperature- and voltage-dependence of the electronic timer). For AM-CW systems it is reasonable to extend the distance calibration model by a cyclic correction term, which contains an amplitude and a phase parameter in order to compensate for deviations caused by internal instrument signal interactions. Details about the physical reasons can be found for example in Joeckel & Stober (2002).

According to Lichti (2007) additional distance parameters are termed as a_i , additional horizontal angle parameters as b_i and additional vertical angle parameters as c_i .

The following calibration model (compare Fig. 2) was considered in the developed software and contains all parameters – independent whether they can be determined or

not and whether they are reasonable for the investigated laser scanner system:

$$\Delta D = a_0 + a_1 D + a_2 D^2 + a_3 e^{-a_4 D} \sin\left((D - a_5) \frac{2\pi}{a_6}\right) \quad (3)$$

Equation (3) contains the following parameters, their possible physical reasons are indicated in brackets:

- a_0 = additive correction (constant part of zero point deviation)
- a_1 = scale correction (frequency deviation, linear part of zero point deviation)
- a_2 = quadratic correction (quadratic part of zero point deviation)
- a_3, a_5, a_6 = amplitude, frequency and phase of cyclic correction (only for AM-CW systems)
- a_4 = attenuation of cyclic correction

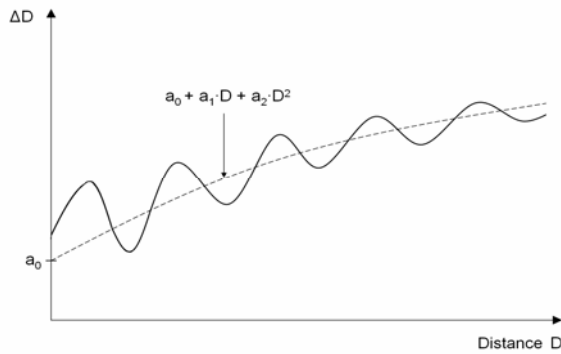


Figure 2. Theoretic distance calibration model

Further empirical parameters which were presented by Lichti (2007) were also considered but subsequently omitted as they were not found significantly with the investigated laser scanner system.

An interesting model extension is the consideration of the dependence of the measured distance from angle between laser beam and object surface. This effect was determined in Teschke (2004) and will be investigated in future investigations in more detail.

2.3 Additional parameters: horizontal and vertical angle

2.3.1 Axis errors and eccentricities

For geodetic instruments such as theodolites and total stations it is usual to define three axes which should be orthogonal to each other: vertical, trunnion and collimation axis. As this is not completely the case in practise, this leads to the trunnion and collimation axis error. Moreover, the three axes have to intersect in one single point, otherwise there are eccentricities which cause systematic measurement errors (e.g. Deumlich & Staiger (2002)). This coherence can be adapted to terrestrial laser scanner systems as they are construction-wise similar to theodolites and total stations. In geodetic instruments most deviations are compensated by measurements in both positions of the telescope, which is mostly not feasible with terrestrial laser scanners.

Most terrestrial laser scanners determine the horizontal and vertical direction of the laser beam directly by the position of the stepping motors and not by measurements on an internal reference circle (as done with total stations). Therefore the name 'circle eccentricity error' is not really appropriate. However, there are similar effects existing subject to the system construction.

2.3.2 Horizontal angle

The calibration model for the horizontal angle is defined by equation (4). This model based on the model published in Lichti (2007) and contains additional parameters for the compensation of the horizontal circle eccentricity (b_3, b_4) and a parameter for the compensation of the eccentricity of the collimation axis with respect to the vertical axis b_5 .

$$\Delta \alpha = b_1 \sec \beta + b_2 \tan \beta + [b_3 \sin(\alpha) + b_4 \cos(\alpha)] + \arcsin \frac{b_5}{D} + [b_6 \sin(2\alpha) + b_7 \cos(2\alpha)] + b_8 \cos(3\alpha) \quad (4)$$

The following parameters are considered:

- b_1 = collimation axis error
- b_2 = trunnion axis error
- b_3, b_4 = horizontal circle eccentricity
- b_5 = eccentricity of the collimation axis with respect to the vertical axis

The extended geometric calibration model published in Lichti (2007) contains further physical and empirical parameters from which only these three parameters could be found significantly in the investigation with the Riegl LMS-Z420i:

- b_6, b_7 = non-orthogonality of the plane containing the horizontal angle encoder and the vertical axis
- b_8 = empirical parameter for compensation of remaining systematic effects not corrected by the collimation and trunnion axis error parameter (possibly wobbling of the trunnion axis)

2.3.3 Vertical angle

The vertical angle measurements of the Riegl LMS-Z420i could be improved in the investigations described in this paper applying the following calibration model:

$$\Delta \beta = c_0 + [c_1 \sin(\beta) + c_2 \cos(\beta)] + \arcsin \frac{c_3}{D} + c_4 \cos(3\alpha) \quad (5)$$

The vertical angle calibration models contains the following physical defined parameters:

- c_0 = vertical circle index error
- c_1, c_2 = vertical circle eccentricity
- c_3 = eccentricity of the collimation axis with respect to the trunnion axis

Furthermore, only one of the empirical parameters, published in Lichti (2007) could be determined significantly:

- c_4 = empirical parameter to model a sinusoidal error as function of the horizontal direction with period of 120° (cosine term)

3. VALIDATION

3.1 Test fields

The investigation of the compliance of the geometric model with the physical reality of the Riegl laser scanner occurred using two calibration rooms with different dimensions.

Test field 1 is an office with a square area, where distances up to 5 m can be realized. There are ca. 100 signalised targets (diameter: 1 cm) distributed at the walls and the ceiling. The targets are black circles on white background.

Test field 2 is a court yard, which is completely surrounded by 4 facades with a height of 20 m. There are ca. 100 retro-reflective targets (diameter: 5 cm) distributed at the 4 facades. Maximal possible laser scanner distance is ca. 60 m. In both test fields the maximal range of the scanner of 800 m cannot be covered.

3.1.1 Scanning in test field 1

The terrestrial laser scanner was situated in each corner of the room and tilted 45° vertically, in order to allow for the recording of points on the ceiling. Additionally, two scans from the centre of the room were recorded with a tilt angle of 90° . The laser scanner was also rotated 90° horizontally between both scans (Fig. 3).

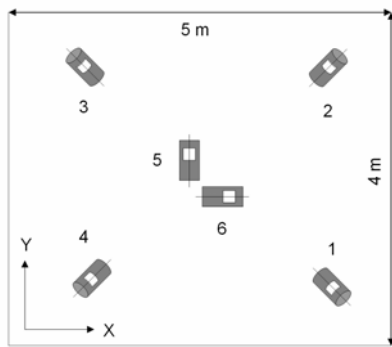


Figure 3. Configuration of laser scanner positions (1)

The angular resolution of the laser scans was 0.035° ($126''$), which corresponds to a scan point distance of 2.5 mm in 4 m distance. For the manual measurement of the target coordinates, the Riegl laser scanner software RiScan Pro was used. As the black circles on white background are distinguishable within the intensity images of the laser scanner, these were used for the coordinate determination by manual selection of the target centre (with integer pixels) and attribution of the associated spherical coordinates.

An automatic target measurement with sub-pixel operators is not supported by the software for this target design. Therefore the lateral accuracy of the spherical laser scanner coordinates is limited by the chosen angular resolution.

The target design (black on white background) turned out to be not really suitable, as the intensity values in the target centre

were very low which often resulted in suboptimal accuracies of the distance determination.

3.1.2 Scanning in test field 2

This test field was scanned three times from different positions which constitute an equilateral triangle (Fig. 4).

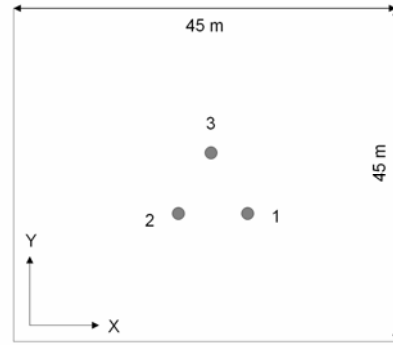


Figure 4. Configuration of laser scanner positions (2)

The centre of the retro-reflective targets were determined automatically applying a centroid operator to the intensity image with intermediate precision.

3.2 Calculation and results

The calibration model described in section 2 was integrated into a bundle adjustment software package, which was originally developed and implemented for a combined analysis of laser scanner data and central-perspective, panoramic and fisheye image data as presented in Schneider & Maas (2007).

The multi-station adjustment is calculated as free network adjustment. Since different types of observations are adjusted simultaneously (distance and angles), it is necessary to assign adequate weights to the laser scanner observations. For this purpose a variance component estimation procedure was implemented in the adjustment in order to obtain independent estimations of the standard deviations of the observations. Thus, the precision characteristics of the different types of laser scanner observations will be optimally utilised and the effect of additional parameters on each type of observation can be investigated separately.

The object coordinates are handled as unknown parameters. Therefore the depth coordinates are determined not only by the distance measurements itself but also by the intersection of rays from different scanner positions to the object point.

3.2.1 Results from test field 1

In a first calculation the additional parameters were included in the geometric model separately and afterwards sorted by the magnitude of their effect on the average standard deviation of the determined object point coordinates (RMS). Subsequently the parameters were included stepwise in the order of their impact on the RMS values (table 1).

The consideration of the vertical circle eccentricity (c_1, c_2) result in an reduction of the estimated standard deviations of the vertical angle observations ($\hat{\delta}_\beta$), which lead to an improvement of the object point coordinates. However, only c_1 could be determined significantly.

The estimated standard deviation of the distance measurements ($\hat{\sigma}_D$) could be improved applying either a_1 (scale) or a_0 (additive correction). This confirms, that the zero point deviation effects particularly short range measurements. If both parameters are estimated in the same calculation, they are highly correlated (97.4 %) due to the low differences of the distance observations (2 – 5 m). It is therefore sufficient to use only one of both parameters. As expected, cyclic distance errors could not be found as the investigated instrument is a time-of-flight laser scanner.

Finally, additional horizontal angle parameters were considered. The horizontal circle eccentricity (only b_4 term), the eccentricity of the collimation axis with respect to the vertical axis (b_5) as well as the collimation axis error (b_1) have a positive influence on the estimated standard deviations of the horizontal angle ($\hat{\sigma}_\alpha$). The estimated standard deviations of the object coordinates (RMS) cannot be further reduced.

Parameter	$\hat{\sigma}_D$ [mm]	$\hat{\sigma}_\alpha$ [“]	$\hat{\sigma}_\beta$ [“]	RMS _{XYZ} [mm]
basic model only	13.28	52.75	68.10	1.44
+ $c_1, (c_2)$	13.03	52.46	51.13	1.22
+ c_3	12.92	52.00	49.90	1.19
+ a_1	8.81	51.90	49.67	1.16
+ a_0	8.75	51.94	49.64	1.16
+ (b_3), b_4	8.79	50.12	49.57	1.15
+ b_5	8.73	48.63	49.28	1.13
+ b_1	8.74	47.98	49.41	1.13

Table 1. Stepwise addition of calibration parameters (1)

Altogether the estimated standard deviations were improved applying additional parameters about 34 % (distance), 9 % (horizontal angle) and 27 % (vertical angle).

Table 2 compiles the additional parameters together with their estimated standard deviations which could be estimated significantly in the bundle adjustment, including parameters which have no effect on the estimated standard deviation of the observations.

Furthermore the significance levels were calculated for each parameter. According to that, the eccentricities of the collimation axis (b_5, c_3) as well as the vertical circle eccentricity (c_1) are very significant (99.9 %), the additional distance parameters, the collimation axis error as well as the horizontal circle eccentricity are significant (99.0 %) and the parameters b_7 and b_8 low significant (80 %).

Parameter	Value	Standard deviation	Significance
a_0	4.91 mm	1.75	99 %
a_1	0.00148	0.00050	99 %
b_1	-132.01 “	51.57 “	99 %
b_4	-109.32 “	37.13 “	99 %
b_5	1.69 mm	0.42 mm	99.9 %
b_7	-146.45 “	99.01 “	80 %
b_8	70.13 “	45.38 “	80 %
c_1	177.39 “	12.38 “	99.9 %
c_3	2.78 mm	0.81 mm	99.9 %

Table 2. Estimated calibration parameters (1)

3.2.2 Results from test field 2

The same investigations as in test field 1 were carried out using the observations recorded in test field 2. At first a calculation without any additional parameters were processed (table 3). Thereafter the same additional parameters were applied as done in the previous section. Thus, the estimation of the standard deviation of the distance and horizontal angle observation was improved about 17 % and the standard deviation of the vertical angle about 11 %. The effect of additional parameters here is significant lower compared to the results obtained from test field 1. It is assumed, that the reason can be found in the different measurement ranges. The axis eccentricity parameters are therefore stronger correlated with other parameters (e.g. vertical circle index error c_0).

The collimation axis error b_1 could not be determined as well. This can be traced back to a lack of high vertical angles.

A low improvement of the standard deviations of the observations was achieved by the consideration of b_6 and c_4 .

The correlation between a_0 and a_1 was 100 %. Therefore it was not possible to determine both parameters within the same calculation.

Parameter	$\hat{\sigma}_D$ [mm]	$\hat{\sigma}_\alpha$ [“]	$\hat{\sigma}_\beta$ [“]	RMS _{XYZ} [mm]
basic model only	4.89	19.28	10.27	3.12
+ $c_{T1}, (c_{T2})$	4.64	18.24	9.72	3.12
+ a_0/a_1	4.46	18.99	10.01	2.91
+ (b_3), b_4	4.28	17.37	9.53	2.78
+ b_6	4.27	16.72	9.46	2.81
+ c_0	4.13	16.75	9.23	2.92
+ c_4	4.08	15.94	9.10	2.84

Table 3. Stepwise addition of calibration parameters (2)

Table 4 compiles the parameters which were estimated in the multi-station adjustment including their standard deviations and significance levels. Although the parameters are significant or very significant, the magnitude of the parameter values is low.

Parameter	Value	Standard deviation	Significance
a_0	-2.11 mm	0.34 mm	99.9 %
a_1	0.00011	0.00004	98 %
b_4	-74.26 “	10.31 “	99.9 %
b_6	22.69 “	6.19 “	99.8 %
c_0	148.51 “	35.07 “	99.9 %
c_1	169.14 “	59.82 “	99 %
c_4	10.31 “	2.06 “	99.9 %

Table 4. Estimated calibration parameters (2)

3.2.3 Comparison of results

The standard deviations of the observations, which were estimated in the variance component estimation, are lower as result from the measurements in test field 2 as in test field 1. The reason for this fact is that the observations (spherical coordinates of the target centres) were determined with a sub-pixel operator based on many laser scanner points in test field 2,

but by a manual selection of a single laser scanner point in test field 1. Furthermore, the used angular scan resolution is higher in test field 2 than in test field 1.

The comparison of the estimated additional distance parameters shows significant differences. It is assumed that these deviations have not only instrumental reason, rather this is caused by the different measurement ranges and the different reflection properties of the targets (black-on-white vs. retro-reflective material). Therefore the values are only valid for the current measurement conditions (range, target design,...).

The values of the additional parameters for horizontal and vertical circle eccentricity (b_4 and c_7) are similar in both investigations. Therefore a instrumental reason can be assumed, but confirmed only by more than two independent investigations.

Other parameters cannot be compared, as they were determined significantly either only in the first investigation (test field 1) or only in the second investigation (test field 2).

4. CONCLUSIONS

The investigation on the calibration of the Riegl LMS-Z420i have shown, that it is difficult to calculate reliable and comparable calibration values with the proposed calibration method. The significance of the parameters is often close to the detection limit or parameters cannot be found at all. The determination of calibration values in regular intervals and their automatic application on the measurements, which is usual with geodetic total stations, seems not to be useful for terrestrial laser scanners. This has to be traced back to the problem of the unknown calibration model which is already applied within the instrument itself and which cannot be deactivated and the precision of the observations which is not always sufficient to determine the parameters significantly. Another reason is that the parameters are not only effected by the instrument but also depend on the external measurement conditions such as measurement range, target design, angle between laser beam and object surface and the chosen angular resolution.

However, the precision of the calculation results could be increased up to 30 % using additional parameters within the geometric model. This shows that the calibration model is valid at least for all laser scans under the same conditions. This argues for the benefit of an 'on-the-job' calibration based on a multi-station adjustment and a geometric model with additional parameters. It has to be decided in practise individually, whether it is reasonable or possible, to estimate calibration parameters simultaneously with the laser scanner project.

Nevertheless it is desirable that laser scanner manufacturers disclose their calibration models to the users which would enable a standardisation of the calibration of terrestrial laser scanners. This would allow the user for an assessment of the measurements regarding precision, reliability and stability.

The proposed calibration method can be extended if images (central perspective, fisheye or panoramic) are used within the laser scanner project additionally, for example for texturing purposes. These images can be comprised in the calibration procedure. This means that scanner and camera aid one another in the self-calibration.

5. REFERENCES

Amiri Parian & Grün, 2005. Integrated laser scanner and intensity image calibration and accuracy assessment.

International archives of Photogrammetry, Remote Sensing and Spatial Information Sciences. Vol. XXXVI, Part 3/W19.

Deumlich, F. & Staiger, R., 2002. Instrumentenkunde der Vermessungstechnik. 9th Edition, Herbert Wichmann Verlag, Heidelberg.

Joeckel, R., Stober, M., 1999. Elektronische Entfernungs- und Richtungsmessung. 4th Edition, Wittwer Verlag, Stuttgart.

Lichti, D. & Franke, J., 2005. Self-calibration of the IQSun880 laser scanner. Eds. Grün, A; Kahmen H., Optical 3-D Measurement Techniques VII.

Lichti, D., 2007. Error modelling, calibration and analysis of an AM-CW terrestrial laser scanner system. *ISPRS Journal of Photogrammetry & Remote Sensing*, 61, pp. 307-324.

Lindenbergh, R., Pfeifer, N., Rabbani, T. (2005). Accuracy analysis of the Leica HDS3000 and feasibility of tunnel deformation monitoring. *Proc. of ISPRS Workshop Laser scanning 2005*. Eds.: Vosselman, G.; Brenner C., *International Archives of Photogrammetry, Vol. XXXVI, Part 3/W19*.

Neitzel, 2006. Investigations of axes errors of terrestrial laser scanners. *5th International Symposium Turkish-German Joint Geodetic Days, Berlin*.

Reshetyuk, Y., 2006. Investigation and calibration of pulsed time-of-flight terrestrial laser scanners. *Licentiate theses in Geodesy. Royal Institute of Technology, Stockholm*.

Riegl laser measurement GmbH, 2007. Data Sheet LMS-Z420i – Long range & high accuracy 3D terrestrial laser scanner system. http://www.riegl.com/terrestrial_scanners/lmsz420i/_datasheet_lmsz420i.pdf (accessed 23 April 2008).

Rietdorf, 2005. Automatisierte Auswertung und Kalibrierung von scannenden Messsystemen mit tachymetrischem Messprinzip. *Dissertation TU Berlin. Deutsche Geodätische Kommission. Verlag der Bayerischen Akademie der Wissenschaften*.

Schneider, D., 2006. Terrestrial laserscanning for area based deformation analysis of towers and water dams. *Proceedings of 3rd IAG Symposium on Geodesy for Geotechnical and Structural Engineering & 12th FIG Symposium on Deformation Measurement*, Eds.: H. Kahmen, A. Chrzanowksi.

Schneider, D., Maas, H.-G., 2007. Integrated Bundle Adjustment of Terrestrial Laser Scanner Data and Image Data with Variance Component Estimation. *The Photogrammetric Journal of Finland, Volume 20/2007, pp. 5 – 15*.

Schneider, D., Schwalbe, E., 2008. Integrated processing of terrestrial laser scanner data and fisheye-camera image data. *XXIth ISPRS Congress, Beijing, China. International Archives of Photogrammetry, Remote Sensing and Spatial Information Science, Volume XXXVII, Part B5*.

Teschke, 2004. Genauigkeitsuntersuchung des terrestrischen Laserscanners Riegl LMS-Z420i. *Diplomarbeit Technische Universität Dresden, Institute of Photogrammetry and Remote Sensing*.