CALIBRATION OF TERRESTRIAL LASER SCANNERS FOR THE PURPOSES OF GEODETIC ENGINEERING

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Abstract: In order to achieve the results that meet specifications of a given project the knowledge of the accuracy of the surveying equipment is inevitable. Standard calibration models and procedures exist for all traditional geodetic and photogrammetric instruments, and they should also be developed for terrestrial laser scanners (TLS), a new surveying technique. This is especially important for using TLS in high-precision applications, like engineering surveys and deformation measurements. The development of such models and procedures, available to users, is carried out within a research project at the Geodesy Division of the Royal Institute of Technology (KTH). Three scanners – Callidus 1.1, Leica HDS 3000 and Leica HDS 2500 (the latter is owned by the Division) – have been investigated at the specially established indoor 3D calibration field, following the common routine. The main interest was to investigate the systematic instrumental errors. The knowledge of these errors is rather limited due to the proprietary design of the scanners. Our approach was to first perform scanner self-calibration, assuming that the systematic instrumental errors were the same as those in the total station, and then to compare the distances, horizontal directions and vertical angles derived from the scanning with the true ones in order to reveal the possible presence of some non-modelled systematic trends. We have found a significant vertical scale error in the scanner Callidus 1.1. We have also investigated the target coordinate accuracy, stability of the range measurements over time (range drift) and angular accuracy and precision. The results are believed to give a good insight into the inner working of TLS and a grounded estimate of their performance. They also provide a good base for comparison of different scanning systems and the development of standardized calibration models and procedures for TLS.

1. Introduction

Terrestrial laser scanning (TLS) is an innovative surveying technology allowing the user to capture large amounts of 3D data directly, rapidly and with high accuracy. However, the wider market acceptance of the scanners is inhibited by the unpredicted performance and absence of the standardized calibration procedures, which complicates comparison of the scanners of different brands. The producers' specifications are based on proprietary calibration routines and, besides, cannot be completely relied on. Not much is known about the inner performance of the scanners and the systematic instrumental errors. For this reason, it is important to investigate the scanners to obtain independent accuracy/precision estimates and develop standardized calibration models and procedures. Many tests have been conducted in the last 5 years, e.g. [3]. They comprised mainly the investigation of the scanner accuracy and comparison of performance of different scanners using reference target fields and reference objects. In fact, this idea is not new. It has been employed for the tests of laser range imaging devices, the predecessors of modern laser scanners, in the 1990s (e.g. [12]). [14] and [15] investigated in more detail the instrumental errors in the scanner Imager 5003. Several publications have been devoted to the full instrument self-calibration [1], [10] and [13]. The research work is now under way at the Geodesy Division of the Royal Institute of Technology (KTH), aimed, among other things, at the development of the calibration models and procedures for TLS, available to users. Three scanners – Callidus 1.1, Leica HDS 3000 and Leica HDS 2500 – have been tested at the specially established indoor 3D calibration field. We investigated the systematic instrumental errors (in the following, they will be referred to as calibration parameters), target coordinate accuracy in the point clouds, stability of the range measurements over time (range drift) and angular precision and accuracy. This paper highlights the main results achieved in the course of the research work.

2. The Laser Scanner Calibration Field

A calibration field for the investigations of TLS has been established in one of the rooms of the Division. The layout of the field is shown in Figure 1. The room contains also a photogrammetric calibration field.

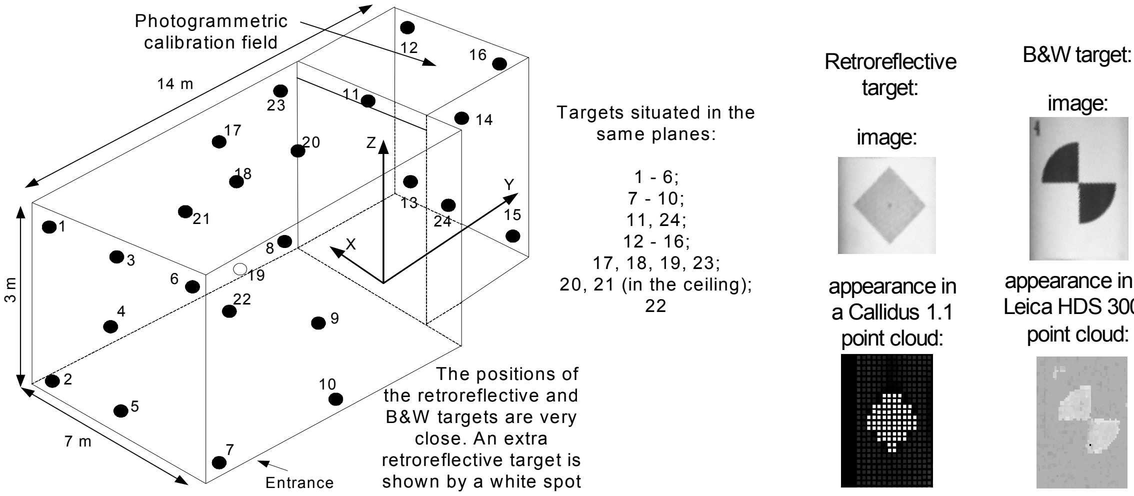

Figure 1: Left: layout of the KTH calibration field and its coordinate system (left-handed). Right: targets used in the tests and their appearance in the point clouds

The calibration field includes two target arrays (see also Figure 1):

- 24 rhomb-shaped retroreflective targets, size 10x10 cm. This target array was used for the calibration of the scanner Callidus 1.1;
- 23 black-and-white (B&W) HDS targets printed on paper. This target array was used for the calibration of the scanners Leica HDS 3000 and Leica HDS 2500;

All the targets are placed on the walls and ceiling and distributed over the whole volume of the room. To provide the durability of the targets, none of them has been placed on the floor. Both arrays have been surveyed with the total station Geodimeter 640M. The standard deviations of the adjusted target coordinates, computed in Topocad, were less than 0.5 mm in each coordinate direction. Therefore, a reliable external reference has been established.

3. Description of the Experiments

The scanners Callidus 1.1 and Leica HDS 3000, provided by the vendors, were investigated in November and December 2004, respectively. The scanner Leica HDS 2500 was acquired by the Geodesy Division in April 2005 and the tests were made in June 2005. Before the latter investigations, the B&W target array was re-surveyed, and the coordinate precision after adjustment was comparable to that mentioned in the Section 2. During the experiments, a number of scans were made with each scanner set up at different locations within the calibration field. The particulars of the scans are given in Table 1.

Scanner	No. of the targets in the point cloud	No. of scans	Resolution (hor°./vert°. or mm x mm)
Callidus 1.1	17, 17 and 16	1 scan each	0.125°/0.25°; 0.25°/0.25°; 0.25°/0.25° (5 scans averaged)
	7 (used in the angular precision and accuracy tests)	3	0.25°/0.25°
Leica HDS 3000	21, 23 7, 9, 8 and 10	1 scan each	10 x 10 mm 15 x 15 mm
	7 (used in the angular precision and accuracy tests)	6	5 x 5 mm
Leica HDS 2500	6, 6, 5, 5, 4 and 4	1 scan each	Same
	5 (used in the angular precision and accuracy tests)	3	Same

Table 1: Particulars of the scans taken during the experiments

We took scans of different resolution and the number of scans averaged with Callidus 1.1 in order to study how these options influenced the scanner precision. The position of the centre of this scanner in the calibration field (external) coordinate system at each of the setups was determined with a total station Geodimeter 640M. Due to the time constraints, the position of the centre of the scanner Leica HDS 3000 in the external system has been determined only when taking 6 scans of the 7-target array. At each setup, this scanner was levelled with the aid of the bull's-eye level as carefully as possible. After the scanning, the coordinates of the centres of the retroreflective targets were computed in MATLAB® as means of the *XYZ* coordinates of the responses (the points of the beam reflection) from the targets, extracted in the software 3D-Extractor. The coordinates of the centres of the B&W HDS targets were computed by fitting these targets to the point clouds in the software Cyclone. In some scans, fitting was made after fine scanning of the targets, in the others the targets were fitted directly to the point clouds. Although these targets are designed for a phase-based scanner Leica HDS 4500, most of them have been successfully recognized in the scans taken with Leica HDS 3000 and Leica HDS 2500 (some problems occurred only at steep incidence angles).

3.1. Estimation of the calibration parameters and target coordinate accuracy

We performed self-calibration of each scanner in MATLAB®, where we estimated the Helmert transformation parameters between the scanner and external coordinate systems for all the scans taken, and the calibration parameters, in a parametric least squares (LS) adjustment. We have not estimated the scale factor since the distances from the scanner to the targets were not longer than 10 m, and the scale factor could thus not be estimated reliably. We have neither estimated the translation parameters for Callidus 1.1 as well as for the 6 scans of the 7-target array taken with Leica HDS 3000 (Table 1) since the coordinates of the scanner centre in the external system in these cases were known. As in many other investigations of TLS, we assumed that the scanner calibration parameters were similar to those encountered in a total station – zero error (additive constant) k_0, collimation and horizontal axis errors, c and i, respectively, and the vertical index error ζ [7]. The approach we employed was similar to [10]. The mathematical model used looks as follows:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{bmatrix} + \mathbf{R}(\alpha_1, \alpha_2, \alpha_3) \begin{bmatrix} x \\ y \\ z \end{bmatrix}; \quad \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} (r_{scan} + k_0)\cos(\varphi_{scan} + (c) + (i))\cos(\theta_{scan} + \zeta) \\ (r_{scan} + k_0)\sin(\varphi_{scan} + (c) + (i))\cos(\theta_{scan} + \zeta) \\ (r_{scan} + k_0)\sin(\theta_{scan} + \zeta) \end{bmatrix} \tag{1}$$

where $[X \quad Y \quad Z]^{\mathrm{T}}$ and $[x \quad y \quad z]^{\mathrm{T}}$ are the coordinates of the target centres in the external and scanner coordinate systems, referred in the following to as "true" and "scan", respectively, $[\Delta X \quad \Delta Y \quad \Delta Z]^{\mathrm{T}}$ is the vector of Helmert translation parameters, $\mathbf{R}(\alpha_1, \alpha_2, \alpha_3)$ is the rotation matrix between the two systems, r_{scan}, φ_{scan} and θ_{scan} are the measured ("scan") distances, horizontal directions and vertical angles, respectively, and [7]

$$(c) = c / \cos\theta_{scan}, \quad (i) = i \tan\theta_{scan} \tag{2}$$

The above-mentioned assumption is however true only as a first approximation since the laser scanners are designed in a completely different way from the total stations. Therefore after the self-calibration we computed the "true" distances r_{true}, horizontal directions φ_{true} and vertical angles θ_{true} using the "true" coordinates of the targets. Then we analyzed the differences between the corresponding "scan" and "true" quantities, which can be roughly regarded as "errors", to reveal some non-modelled systematic trends. It was, however, rather inconvenient to compare directly φ_{scan} and φ_{true}, due to the orientation unknowns in each scan. Therefore, the coordinates of the targets were first transformed from the scanner into the external coordinate system using the estimated Helmert parameters. With these "transformed" coordinates, we computed the "transformed" horizontal directions and vertical angles, φ_{transf} and θ_{transf}, respectively. Analyzing the data from Leica HDS 3000, we discovered that the magnitude of the vertical angle "errors" varied with the sine of φ_{transf} due to the non-precise levelling of the scanner with the bull's-eye level (the scanner is not equipped with a dual-axis compensator). This complicated the estimation of the calibration parameters. Using θ_{transf} solved this problem; in a way, "analytical levelling" of the scanner has been made. In the way described above, we tried to model empirically the calibration parameters the physical cause for which could not be explained by the existing total station instrumental error model. If any systematic trends were discovered, the new parameters were included in the self-calibration. This procedure continued until no significant systematic trends remained. During the self-calibration, the "corrected" "scan" target coordinates were computed from r_{scan}, φ_{scan} and θ_{scan} and using the estimated calibration parameters. The variance-covariance matrix $\mathbf{C}$ of the "observations" in the self-calibration has been computed as follows:

$$\mathbf{C} = \mathbf{C_{XYZ}} + \mathbf{R}(\alpha_1, \alpha_2, \alpha_3)\mathbf{J}\mathbf{C_{instr}}\mathbf{J}^{\mathrm{T}}\mathbf{R}(\alpha_1, \alpha_2, \alpha_3)^{\mathrm{T}} \tag{3}$$

where $\mathbf{R}(\alpha_1, \alpha_2, \alpha_3)$ is as defined before, $\mathbf{J}$ is the Jacobian matrix of the derivatives of $[x \quad y \quad z]^{\mathrm{T}}$ with respect to r_{scan}, φ_{scan}, θ_{scan}, $\mathbf{C_{XYZ}}$ is the (diagonal) variance-covariance matrix of the "true" target coordinates and

$$\mathbf{C_{instr}} = diag\left(\sigma_r^2, \quad \sigma_\varphi^2, \quad \sigma_\theta^2\right). \tag{4}$$

Here σ_r, σ_φ and σ_θ are the accuracies of r_{scan}, φ_{scan} and θ_{scan}, respectively, reported by the manufacturers. The *a priori* standard deviation of unit weight σ_0 was set to 1. Obviously, the above-mentioned way of computing the *a priori* variance-covariance matrix is not without drawbacks since the manufacturers' specifications refer to *single* point measurements, while we estimate the position of the target centre from a number of points. In the course of the self-calibration, we revealed that the parameters *c* and α_3 were highly correlated, for all the three scanners tested. In order to reduce the correlation, we chose a target at each scan at about the instrument height (θ_{scan} < 1º), and imposed a constraint $(c) = 0$ for this target. After the LS adjustment, we carried out the global test on the goodness of the fit and outlier detection with the Danish method. The *a posteriori* standard deviation of unit weight $\hat{\sigma}_0$ was statistically different from 1 in all cases. If no outliers were detected, then the variance-covariance matrix **C** was scaled by $\hat{\sigma}_0^2$ and a new adjustment was made [9]. Otherwise, the adjustment was carried out using the weight matrix computed with the Danish method.

The precisions of the Helmert parameters and the residuals of the self-calibration give a good indication of the precision of the scanner (cf. [2]). In addition to the residuals of the self-calibration along each of the coordinate axes, we computed the "3D residuals" ε_{3D} as follows (cf. [2]):

$$\varepsilon_{3D} = \sqrt{\varepsilon_X^2 + \varepsilon_Y^2 + \varepsilon_Z^2} \tag{5}$$

where ε_X, ε_Y and ε_Z are the residuals along the respective coordinate axes. The values of ε_{3D} give a good idea about the "total" 3D target coordinate precision achieved with a particular scanner. The target coordinate accuracy can be estimated in the following way. After the self-calibration we computed the distances between each pair of the targets in each of the scans using the "scan" ("corrected") and "true" coordinates of the targets. The target coordinate accuracy was then computed as follows (cf. [5]):

$$\sigma_{t\arg i} = \sqrt{(d_{scan\,ij} - d_{true\,ij})^2 / 2} \tag{6}$$

where $\sigma_{targ\ i}$ is the accuracy of the coordinates of the *i*-th target and $d_{scan\ ij}$ and $d_{true\ ij}$ are the "scan" and "true" distances, respectively, between the targets *i* and *j*.

3.2. Investigation of the range drift

The quality of the range measurements in TLS may be affected by the temperature drift of the laser rangfinder, when the temperature inside the scanner is not constant during a scanning session. The investigations of [4] revealed a significant range drift in their scanning laser rangefinder Perceptron. Variations in the measured range with time have also been observed in [15] for the scanner Imager 5003. In order to study this phenomenon, a target (retroreflective for Callidus 1.1, B&W and HDS square tilt-and-turn targets for Leica HDS 3000 and B&W and HDS square planar adhesive targets for Leica HDS 2500) located at about the instrument height and normal incidence was repeatedly scanned during about 3 hours (1.5 hours for HDS 3000, due to the time constraints) at about 5 min intervals (10 min intervals for Callidus 1.1). The range from the scanner to the target (about 5 m) was computed for each time interval. In all cases, the scanner was turned on first time on that particular day. The temperature at the calibration field during the experiments was stable (around 20ºC).

3.3. Investigation of the angular precision and accuracy

The scanners Callidus 1.1 and Leica HDS 3000 were set up in front of the target array 1 – 7 (see Figure 1), at about 3 m from the latter, and 3 scans of the array were made. The position of the scanner centre in the external coordinate system has been determined in both cases. Additionally, the scanner Leica HDS 3000 was rotated by about 180º from the previous position and re-centred, and 3 more scans of the target array were made. The "scan" and "true" horizontal and vertical angles between each pair of the targets, with the vertex at the scanner centre, have been computed using the "scan" and "true" target coordinates, respectively. For the tests of the scanner Leica HDS 2500 we used a different target array, 12 – 16 (see Figure 1), since the previous one was partially blocked by the stuff brought to the calibration field after the first tests. Since it is impossible to set up this scanner over a known point and level, the "scan" and "true" distances, not angles, between each pair of the targets were computed using the "transformed" and "true" target coordinates, respectively. Based on the computed angles and distances, we estimated the precision and accuracy of the horizontal and vertical angles for the three scanners.

4. Results

4.1. Scanner self-calibration and target coordinate accuracy

The minimum and maximum standard deviations of the Helmert parameters estimated in the self-calibration are given in Table 2.

Helmert parameters	**Callidus 1.1**		**Leica HDS 3000**		**Leica HDS 2500**	
	Min	**Max**	**Min**	**Max**	**Min**	**Max**
Translations, mm:						
ΔX	Not estimated		0.3	0.7	0.2	1.2
ΔY			0.3	0.6	0.2	0.7
ΔZ			0.5	1.3	0.4	4.7
Rotation angles ($\alpha_1, \alpha_2, \alpha_3$) , °	0.010	0.022	0.005	0.029	0.003	0.034

Table 2: Precision of the Helmert transformation parameters estimated in the self-calibration

In general, the precision of the rotation angles for the Leica-scanners is better than that for Callidus 1.1, although the maximum standard deviations of ($\alpha_1, \alpha_2, \alpha_3$) in Table 2 are of the same magnitude for the three scanners. The standard deviation of ΔZ parameter for the Leica-scanners is generally larger than that of ΔX and ΔY, which may point to the presence of systematic errors in the vertical angles. The distribution of the residuals of the self-calibration and the "3D residuals" is shown in Figure 2. As one can see, the residuals are approximately normally distributed with zero means, for each scanner. Based on the analysis of Figure 2 one may state that the precision of the Leica-scanners is higher than that of Callidus 1.1. However, it is important to remember that the precisions of the transformation parameters and magnitudes of the residuals are functions not only of the measuring accuracy of the scanner but also of the reduction process involved in the computation of the coordinates of the centres of the targets [11]. Since these were computed from a much larger number of responses in case with the Leica-scanners, than with Callidus, the results are naturally better for the former. No improvement in the precision has been observed when using higher horizontal resolution or averaging 5 scans for Callidus.

Analysis of the "errors" in the vertical angles measured with Callidus 1.1 has shown that the they grew linearly with the increase in the vertical angle (Figure 3). We call this error a "vertical scale error". One possible physical cause for this error is the maladjustment of the angular increment of the polygonal scanning mirror, used in Callidus. Since the vertical angle is computed as a sum of the mirror increments, a constant deviation from the nominal increment of 0.25° (used in our case) introduces a scale error into the vertical angles, whose behaviour is the same as that presented in Figure 3. After this error has been modelled and estimated in the self-calibration, no systematic trend remained in the data (Figure 3).

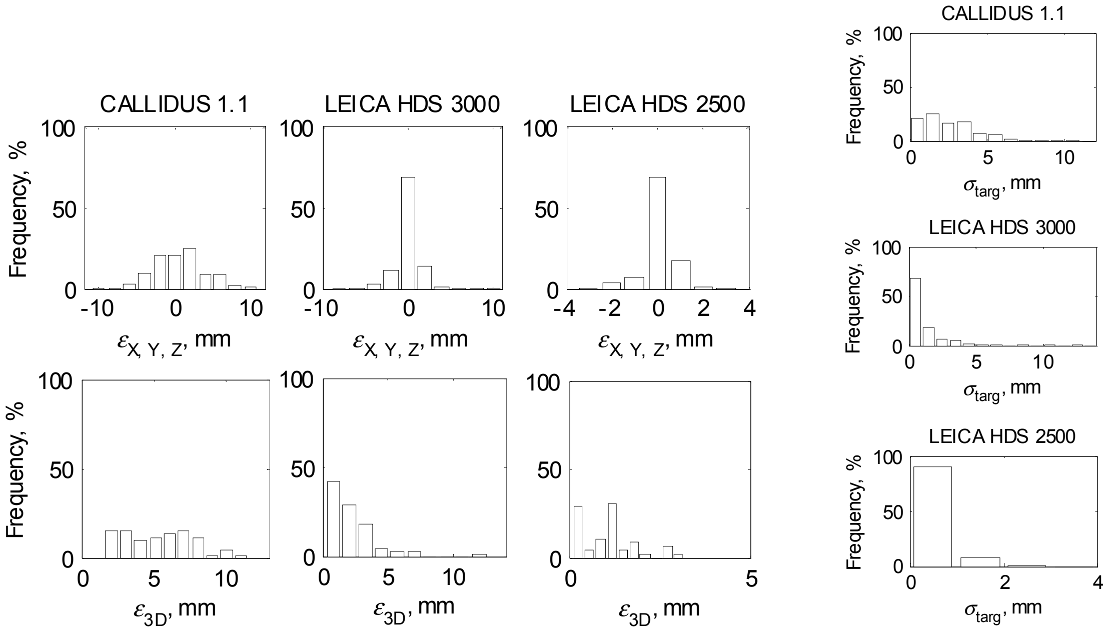

Figure 2: Left: distribution of the residuals of the self-calibration and the “3D residuals”; right: distribution of the values of the target coordinate accuracy

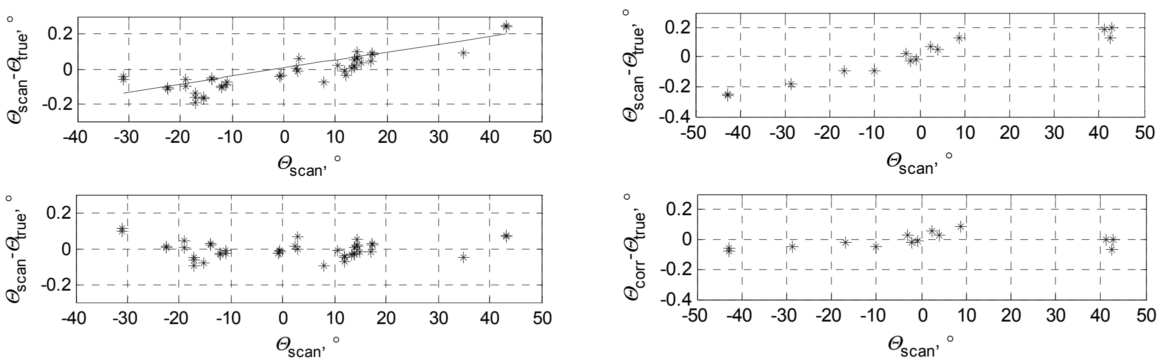

Figure 3: Left: top – “errors” in the vertical angles for the scanner Callidus 1.1 and the correction model fitted, bottom – residuals after the self-calibration. Right: top – “errors” in the vertical angles from the independent dataset, bottom – results of the application of the error model for the vertical angles to this dataset

This model has also been verified by applying it to an independent dataset. We made several scans, from different setups, of the targets well distributed in the vertical dimension, computed θ_{scan} and θ_{true} and then corrected θ_{scan} for the vertical index and scale errors. The results are also shown in Figure 3: the linear trend present in the data has been successfully removed with the proposed model. Otherwise, no systematic trends have been observed in this and the Leica HDS scanners.

The final set of the calibration parameters and their standard deviations (1 sigma) for the three scanners are shown in Table 3. It should be noted that, due to the geometry of the setups, significant correlation was still present between c and α_3 for Callidus 1.1 and Leica HDS 3000 (the correlation coefficient r is up to 0.85 and 0.88, respectively), between ΔZ and ζ for Leica HDS 3000 (r is up to -0.78) and between α_1 and ζ for Leica HDS 2500 (r is up to -0.91).

Significance of the calibration parameters is shown in the third column for each scanner in Table 3. It has been estimated at 99% confidence level using a *t*-test. According to its results, the significant parameters are the vertical scale error in Callidus 1.1, vertical index error in Leica HDS 3000 and horizontal axis error in Leica HDS 2500. The reason for the vertical index error can be a mechanical miss-alignment of the mirror and the encoder or a zero-shift within the analogue-to-digital (A/D) converter [8]. Finally, the target coordinate accuracy after the self-calibration has been estimated using Eq. (6). The results are shown in Figure 2 (right). The highest accuracy, mostly below 2 mm, is achieved with the scanner Leica HDS 2500. Thus, despite this scanner is not very popular today due to the limited (40x40º) field-of-view (FOV), it appears to be the most accurate among the three scanners tested. The values of $\sigma_{targ\ i}$ can be regarded as good indicators of the scanner accuracy, across the entire FOV since they incorporate nearly all potential sources of error [6].

Calibration parameters	CALLIDUS 1.1			LEICA HDS 3000			LEICA HDS 2500		
	Value	**σ**	**S**	**Value**	**σ**	**S**	**Value**	**σ**	**S**
Zero error, mm	3.3	2.0	N	-0.2	0.1	N	0.5	0.3	N
Collimation error *c*, º	0.033	0.016	N	-0.002	0.006	N	0.001	0.001	N
Horizontal axis error *i*, º	0.013	0.016	N	0.006	0.009	N	0.010	0.003	Y
Vertical index error *ζ*, º	-0.005	0.005	N	0.015	0.005	Y	-0.019	0.008	N
Vertical scale error	-0.0045	0.0002	Y	-	-	-	-	-	-

Table 3: Calibration parameters for the three scanners investigated. S – significance (yes/no)

4.2. The range drift

The changes in the measured range to the target with time, for the three scanners tested, are plotted in Figure 4. The records of the inner scanner temperature were available only for Callidus 1.1. As one can see, the measured range decreases with time for Callidus 1.1 and Leica HDS 3000 and increases for Leica HDS 2500. The range measurements for Callidus are rather noisy but the decrease is obvious. Please note a sudden drop (by about 2.5 mm) in the measured range for Leica HDS 3000 by the end of the first hour of scanning. For all the three scanners, the drift in the measured range is up to 3 mm, which may be considerable for high-precision work. The reason for the range drift is assumed to be the change in the temperature inside the scanner.

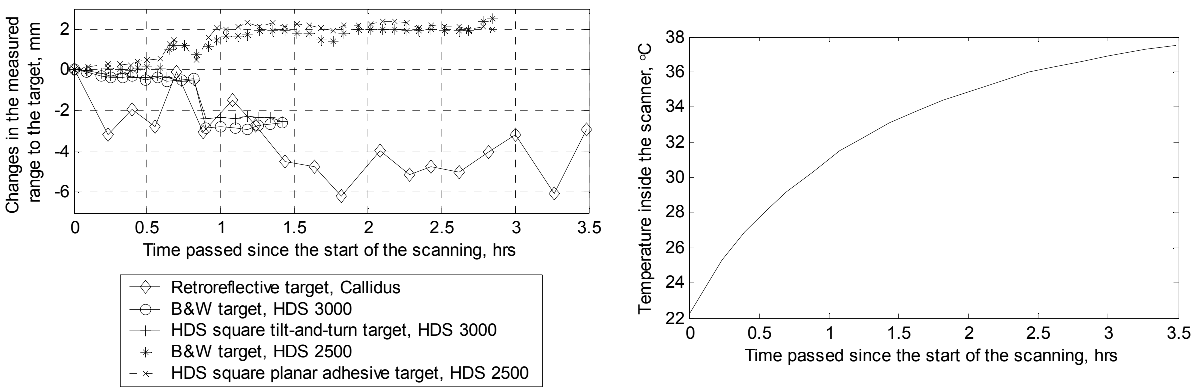

Figure 4: Left: changes in the measured range with time for the three scanners tested; right: changes in the temperature inside the scanner Callidus 1.1 during the scanning session

4.3. Angular precision and accuracy

The estimates of the angular precision (internal standard deviation) and accuracy for three scanners are given in Table 4.

Scanner		CALLIDUS 1.1	LEICA HDS 3000		LEICA HDS 2500
			1st position	2nd position	
Precision, º	Hor.	0.027	0.0015	0.0016	0.002
	Vert.	0.014	0.0008	0.0009	0.002
Accuracy, º	Hor.	0.069	0.047	0.036	0.010
	Vert.	0.123	0.051	0.053	0.006

Table 4: Angular precision and accuracy estimates for the scanners investigated

Separate estimates have been made for the two positions (differed by about 180º) of Leica HDS 3000 since it was discovered that the mean values of the angles obtained for the two positions varied significantly. The reason is assumed to be the centring errors when re-centring the scanner and non-exact levelling of the latter. As follows from Table 4, the vertical precision is about twice better than the horizontal one for the "panoramic" scanners Callidus 1.1 and Leica HDS 3000, due to the lower inertia of the scanning mirror vs. the servomotor, which is used for the measurements of the horizontal directions in these scanners. The horizontal and vertical angular precision for the scanner Leica HDS 2500 are similar since both horizontal and vertical angles are measured using the scanning mirrors. The estimates of the angular accuracy are influenced by the calibration parameters in the scanners (Table 3). For example, the vertical angular accuracy for Callidus is worse than the horizontal one, due to the influence of the vertical scale error. Again, the results are also influenced by the reduction of many responses to the target centres. This may be the reason why the estimates of the angular precision for Callidus are worse than those for the Leica scanners.

5. Conclusions

The results of the investigations of three commercial TLS have been presented. The calibration parameters have been estimated in the self-calibration using the error model of a total station as the outset, and additional parameters have been modelled empirically based on the analysis of the errors in the measured distances, horizontal directions and vertical angles. A significant vertical scale error not explained by the total station error model has been found in the scanner Callidus 1.1. The target coordinate accuracy, over the whole FOV, achieved with the scanners has been estimated to be mainly below 6 mm for Callidus 1.1, 5 mm for Leica HDS 3000 and 2 mm for Leica HDS 2500. A range drift of about 3 mm within the first few hours of scanning is present in all the three scanners, probably due to the changes in the temperature inside the instruments. The vertical angular precision achieved with Callidus 1.1 and Leica HDS 3000 is better that the horizontal one, while they are the same for Leica HDS 2500. The difference between the horizontal and vertical angular accuracy is influenced by the calibration parameters present in the scanners, and it is the largest for Callidus 1.1. The results of the investigations are believed to contribute to the better knowledge in TLS and to the development of standardized calibration models and procedures for laser scanners.

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