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Reliability of Accuracy-Based Calibration in Quantifying Systematic Errors of Static LiDAR

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Abstract

The calibration of terrestrial laser scanners (TLSs) is crucial for ensuring high-quality 3D data. While system calibration often relies on precision-based methods without reference points, this study explores accuracy-based approaches incorporating reference values. TLS self-calibration was performed using point-based and line-based constraints with reference points established through close-range photogrammetry (CRP). The evaluation assessed calibration parameters (CPs), standard deviation, residuals, and correlation coefficient. Results show that the line-based approach improved accuracy by up to 60%, whereas the point-based method exhibited significant deviations. Consequently, while accuracy-based approaches can enhance TLS self-calibration, the line-based constraint is notably more effective.

Keywords: TLS self-calibration; Close-range photogrammetry; Point-based constraint; Line-based constraint

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1.0 Introduction

Accurate 3D models are essential in social and behavioral sciences, particularly in urban planning, heritage preservation, infrastructure management, and environmental monitoring, as they provide precise spatial data that informs decision-making and ultimately enhances behavioral interventions and planning outcomes through a comprehensive understanding of physical environments (Aryan et al., 2021; Karataş et al., 2022; Y. Zhou et al., 2024). Although various methods for 3D data acquisition exist, including contact and noncontact scanners, terrestrial laser scanners (TLSs) are preferred for their speed and accuracy in capturing detailed 3D information (Medić et al., 2021). Despite advancements in terrestrial laser scanning (TLS) technology, observations from TLSs remain susceptible to errors, including systematic errors that specifically impact the accuracy of measurements and reliability of the 3D models produced.

Based on Figure 1, TLS calibration can be performed through two approaches to address systematic errors in TLS data: component calibration, which requires specialized facilities (Schulz, 2007), and system calibration, which can be performed with minimal equipment through self-calibration (Luhmann et al., 2006). While component calibration involves complex setups to refine individual errors, system calibration through self-calibration is simpler but largely focuses on precision techniques that do not utilize reference points. Despite the

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challenges associated with establishing reference points at the calibration site, it is worthwhile investigating how accuracy-oriented approaches in TLS self-calibration can improve data quality. This is particularly relevant given that incorporating known reference points in the calibration of other optical sensors, such as photogrammetric systems and laser trackers, has proven to improve the derivation of calibration parameters (CPs) (El-Din Fawzy, 2019; Wiśniewski, 2018). Building on these positive results, this study aims to investigates the novel application of accuracy-based approaches that incorporate reference values in TLS self-calibration, utilizing two types of constraints: i) point-based and ii) line-based. To achieve the aim, the first objective evaluates the significance of both precision-based (current practice) and accuracy-based (proposed method) approaches within the point-based method, whereas the second objective investigates the effectiveness of the proposed line-based method using accuracy-based techniques, ensuring a thorough exploration of both methods and their contributions to enhancing TLS calibration outcomes.

2.0 Literature Reviews

In TLS, the raw observations consist of the range (r), horizontal direction (φ), and vertical angle (θ). To enhance the accuracy of these measurements, correction values for systematic errors must be applied (Lichti, 2007). These systematic errors can be identified through an instrument calibration procedure. It involves adjusting the instrument to eliminate or reduce systematic errors that can lead to inaccurate readings. By modelling these errors, calibration ensures that the data collected by the instrument closely reflects the true values of the measured parameters, thereby enhancing the accuracy and reliability of the measurements. In this context, this study focuses on significant systematic error models that are crucial for improving measurement accuracy, detailed as follows:

i. Systematic error model for range

$$\Delta r = a_0 \tag{1}$$

ii. Systematic error model for horizontal angle

$$\Delta\varphi = b_0 \sec\theta + b_1 \tan\theta \tag{2}$$

iii. Systematic error model for vertical angle

$$\Delta\theta = c_0 \tag{3}$$

Where,
a_0 = Constant error
b_0 = Collimation axis error
b_1 = Trunnion axis error
c_0 = Vertical circle index error

This study employs statistical testing to identify these systematic errors, specifically the z-test, which assesses the significance of the parameters affecting scanner observations. The significance is determined using the formula provided by Shatz (2024):

$$z = \frac{X}{\sigma_X} \tag{4}$$

Where,
X = Parameter to be evaluated
σ_X = The standard deviation of parameter

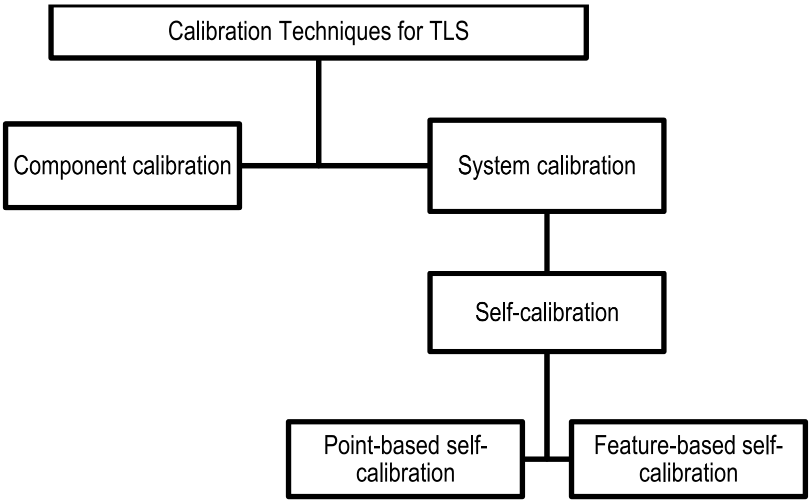


Fig. 1. Calibration techniques for TLS

As shown in Figure 1, the current implementation of point-based self-calibration approach is a precision-based, as it does not utilize known reference values. Although this method has demonstrated improvements in the quality of TLS data, a review of the literature indicates that the incorporation of known reference points in the calibration of other optical sensors, such as photogrammetric systems and laser trackers, significantly enhances the derivation of CPs. For instance, El-Din Fawzy (2019) indicates that employing four control points on a camera calibration sheet, arranged at known distances, enables accurate determination of camera intrinsic parameters, thereby ensuring the photogrammetric model's accuracy. Additionally, M. Wiśniewski (2018) illustrated that integrating a scale bar with a known reference length during laser tracker calibration yielded an average length measurement error of ±0.1 mm, which remained within the manufacturer's maximum permissible error (MPE).

Despite these advancements in related fields, there remains a notable gap in the literature regarding accuracy-based TLS self-calibration. Specifically, there have been no studies investigating the integration of known reference points within the self-calibration process for TLS. With the aim outlined in Section 1.0, it is interesting to explore whether accuracy-based calibration methods can enhance measurement reliability and accuracy in TLS applications. Should this study succeed, it could pave the way for further advancements in TLS calibration techniques, ultimately leading to improved performance and quality in 3D data acquisition. Moreover, such enhancements have the potential to make substantial contributions to the social and behavioural sciences by providing accurate spatial data that informs decision-making processes in various spatial data applications.

3.0 Methodology

This section outlines the methodology employed to ensure accurate and reliable results in the self-calibration of TLS. The selected approach is grounded in established practices in the field, which have been shown to enhance measurement accuracy significantly. The methodology encompasses the establishment of reference values (Section 3.1), the procedure of TLS self-calibration (Section 3.2), and the application of datum constraints in LSA (Section 3.3).

3.1 Establishment of reference values

To examine the applicability of accuracy-oriented approaches in TLS self-calibration, this study was conducted in a standard classroom located at the Star Complex, UITM Arau, Perlis. The classroom, as depicted in Figure 2, measures approximately 12 m (length) x 9 m (width) x 3 m (height), providing an ideal environment for testing due to its controlled setting and consistent geometry. Building on this, photogrammetry measurement was utilized to establish reference values for evaluating the results obtained from point-based and line-based constraints in accuracy self-calibration (ASC) methods due to its capability to achieve accuracy up to 1 mm (Luhmann et al., 2006).

This study conducted two measurements: TLS using a FARO Focus Premium scanner and CRP using a Nikon D7500 camera. To accommodate both measurement types, a specialized target was designed, as shown in Figure 3, to be compatible with both software systems to determine the target centroids: Cyclone for TLS data and Photomodeler Scanner for CRP data. Additionally, to ensure the accuracy of the CRP data, four strategically positioned scale bars were installed on each wall of the classroom, as indicated by the red and blue rectangles in Figure 2.

While the controlled indoor setting offers consistency for testing, it also presents a limitation. The results obtained may not fully capture challenges encountered in outdoor or more complex environments, such as varying lighting conditions, environmental disturbances (e.g., wind, vibrations), and uneven surfaces. These factors, which were not accounted for in this study, could affect the generalizability of the findings to real-world field conditions.

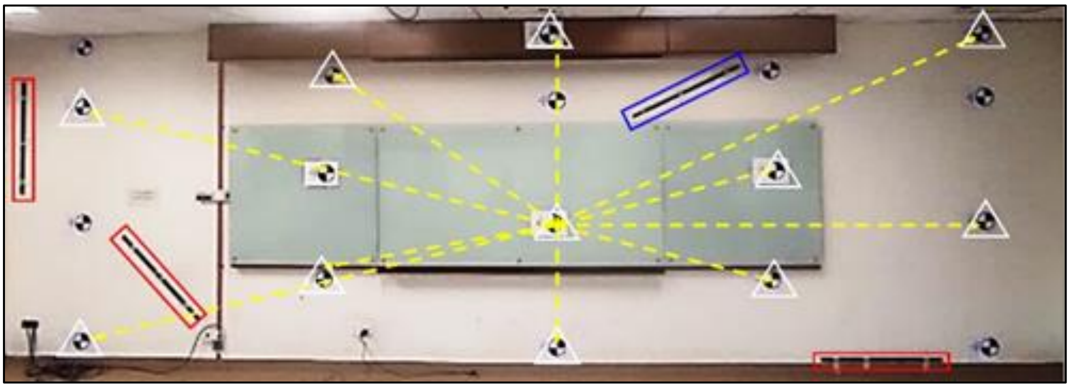


Fig. 2. Ten independent vectors (yellow dashed line) established on Wall D with four scale bars.

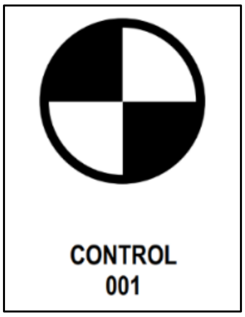


Fig. 3. Specialized target with an outline of the region

3.2 Procedure of self-calibration

The self-calibration process for the Faro Focus Premium scanner was conducted using various self-calibration techniques, which involved strategically distributing 113 specialized targets across the four walls and ceiling of the classroom. This arrangement optimizes data collection and enhances the reliability of the TLS self-calibration process by ensuring comprehensive coverage and effective error modelling. As Lichti (2007) emphasizes, adequate reference targets must be distributed across the scanned surfaces to achieve accurate self-calibration in TLS.

Building on this foundation, the research utilized significant geodetic network design strategies for TLS self-calibration, focusing on both zero-order (ZOD) and first-order design (FOD) approaches, as recommended by Reshetyuk (2009). The zero-order design (ZOD), which emphasizes the definition of the datum, is detailed in Section 3.3. Meanwhile, seven scan stations were employed to assess the scanner's performance based on the first-order design (FOD). Throughout the process, the scanner was positioned equidistantly between the floor and ceiling, and medium-resolution scans were performed consistently to ensure optimal data quality.

3.3 Datum constraints in LSA

Least Squares Adjustment (LSA) is a well-established statistical technique that estimates unknown parameters by minimizing the sum of squared residuals, ensuring the model's parameters align as closely as possible with the observed data. In geodetic adjustments, datum constraints are employed to refine this process further. These constraints may fix the positions of certain control points or the orientation of the coordinate system. By applying datum constraints during the adjustment computation, the solution can be aligned with known reference values, thereby enhancing the accuracy and reliability of the TLS self-calibration process. To perform LSA, all observation equations are expressed in matrix form. According to Ghilani (2017), the minimised sum of the squared residuals is obtained using the matrices defined in Equation (5):

$$X = (A^T W A)^{-1} A^T W l \tag{5}$$

In this equation, A is the matrix of coefficients derived from the linearized equations, W is the weight matrix for each observation, l is the vector of differences between observed and computed values, and X is the matrix of corrections applied to the approximate coordinates of the stations. To achieve the optimal solution, this adjustment process must be iterated until the corrections to the approximate coordinates become insignificant, due to the nonlinear nature of the equations involved in horizontal adjustments. Initially, the original form of matrix A is specified in Equation (6). However, to perform the constrained adjustment, the matrix A, as defined in Equation (6), requires modification.

$$n^A u = \begin{bmatrix} A_{EO} & A_{CP} & A_{TG} \end{bmatrix} = \begin{bmatrix} A_{EO_1} & 0 & 0 & A_{CP} & A_{TG} \\ 0 & A_{EO_2} & 0 & A_{CP} & A_{TG} \\ 0 & 0 & A_{EO_0} & A_{CP} & A_{TG} \end{bmatrix} \tag{6}$$

In the current TLS self-calibration implementation, the precision-based approach applies minimal constraints by fixing the exterior orientation parameters for the first scanner station. Specifically, six elements of the exterior orientation (EO) are fixed, including three translation parameters (Tx, Ty, Tz) and three rotation parameters (Omega, Phi, Kappa). Therefore, based on the original form of the design matrix A, as shown in Equation (6), the application of minimal constraints is demonstrated through the modified matrices in Equations (7) and (8).

$$n^A u = \left[\overset{\text{Removed}}{\boxed{\begin{matrix} A_{EO_1} \\ 0 \\ 0 \end{matrix}}} \begin{matrix} 0 & 0 & A_{CP} & A_{TG} \\ A_{EO_2} & 0 & A_{CP} & A_{TG} \\ 0 & A_{EO_0} & A_{CP} & A_{TG} \end{matrix} \right] \tag{7}$$

$$n^A u = \begin{bmatrix} 0 & 0 & A_{CP} & A_{TG} \\ A_{EO_2} & 0 & A_{CP} & A_{TG} \\ 0 & A_{EO_0} & A_{CP} & A_{TG} \end{bmatrix} \tag{8}$$

Where,

n = Number of observations
u = Number of unknown parameters
A_{EO} = Design matrix for exterior orientation (EO) parameters
A_{CP} = Design matrix for calibration parameters (CP)

A_{TG} = Design matrix for targets (TG)

Focusing on implementing accuracy-based approaches in TLS self-calibration, this study examines both point-based and line-based constraints. The point-based constraint (ASC), as outlined by Ghilani (2017), involves applying minimal constraints by excluding exterior orientation (EO) and target reference points (TG) from the design matrix A as specified in Equation (9).

$$n^Au = \left[\begin{array}{ccccccccc} \text{Removed} & & & & & & \text{Removed} & & \\ \boxed{A_{EO_1}} & 0 & 0 & A_{CP_1} & 0 & 0 & \boxed{A_{TG_1}} & 0 & 0 \\ \boxed{0} & A_{EO_2} & 0 & 0 & A_{CP_2} & 0 & \boxed{0} & A_{TG_2} & 0 \\ \boxed{0} & 0 & A_{EO_0} & 0 & 0 & A_{CP_3} & \boxed{0} & 0 & A_{TG_3} \end{array}\right] \tag{9}$$

In contrast, the line-based constraint (ASC) is executed using Helmert's method, that was introduced by F. R. Helmert in 1872. Helmert's method, detailed in Equation (10), augments the standard matrix (A^TWA) with constraint equations. A and W represent the design and weight matrices, respectively, and $L_{1/2}$ represents the difference between actual and approximate observations. This method incorporates line constraints into the parametric equations by adding rows C and columns (C^T) , vectors X_2 and L_2 into the standard and constant matrices. For solving the parameter vectors X, the matrices in Equation (18) are arranged as shown in Equation (11). However, X_2 is not employed in the later procedure to derive unknown parameters.

$$\begin{bmatrix} A^TWA & \vdots & C^T \\ \cdots & \cdots & \cdots \\ C & \vdots & 0 \end{bmatrix} \begin{bmatrix} X_1 \\ \cdots \\ X_2 \end{bmatrix} = \begin{bmatrix} A^TWL_1 \\ \cdots \\ L_2 \end{bmatrix} \tag{10}$$

$$\begin{bmatrix} X_1 \\ \cdots \\ X_2 \end{bmatrix} = \begin{bmatrix} A^TWA & \vdots & C^T \\ \cdots & \cdots & \cdots \\ C & \vdots & 0 \end{bmatrix}^{-1} \begin{bmatrix} A^TWL_1 \\ \cdots \\ L_2 \end{bmatrix} \tag{11}$$

4.0 Results and Analysis

This section comprehensively evaluates the TLS calibration techniques employed in this study. The analysis is divided into systematic error assessment (Section 4.1), quality assessment of CRP measurement (Section 4.2), quality assessment of reference CPs (Section 4.3), and evaluation of accuracy-oriented approaches (Section 4.4), which is further divided into similarity analysis (Section 4.4.1) and accuracy assessment (Section 4.4.2).

4.1 Systematic error assessment

To identify the systematic errors in the raw TLS data, this study employed a z-test at a 95% confidence level, as outlined in Equation 4. The systematic errors modelled included a_0, b_0, b_1, and c_0. Table 1 demonstrates that, despite employing various TLS self-calibration techniques, the raw TLS data showed lack of significant systematic errors. This outcome is consistent with expectations for a newly manufactured TLS scanner that has undergone precise factory calibration, effectively minimising the potential for such errors. Based on the preliminary analysis, significant synthetic errors (a_0 = 10 mm, b_0 = b_1 = c_0 = 30") simulating systematic errors were introduced to evaluate the effectiveness of TLS self-calibration techniques (Abd Razak et al., 2023).

Table 1. Significance of CPs in raw TLS data

TLS self-calibration techniques	Calculated z			
	a_0	b_0	b_1	c_0
Precision-oriented	1.34375	-0.00775	0.000	-0.14285
Point-based constraint (ASC)	**4**	1.27586	-1.27118	**-3**
Line-based constraint (ASC)	0.81818	0.03906	-0.03846	-0.125

Bold signifies significant CPs

4.2 Quality Assessment of CRP Measurement

After confirming that significant systematic errors were present in the raw data, the next step was to evaluate the quality of CRP measurements, which serve as the foundation for accurate calibration. Using the CRP approach, 34 well-distributed targets were selected as true values to evaluate different self-calibration techniques in enhancing the quality of scanned data. With the aid of specially designed targets, the average precision obtained from Photomodeler Scanner software for these 34 targets was approximately 1 mm for X, Y, and Z precision (refer to Figure 4). Notably, target 11 exhibited the highest precision values in the X and Z coordinates (1.385453 and 1.631969, respectively), likely due to a high incidence angle, as it was located at the edge of the wall (Abbas et al., 2019). The differences between the known and measured lengths of the scale bars were computed to ensure the accuracy of the established true values. The observed length discrepancies of 0.28 mm for wall A, 0.98 mm for wall B, 0.87 mm for wall C, and 0.65 mm for wall D demonstrated the reliability of the true values and reference constraints established using the CRP method.

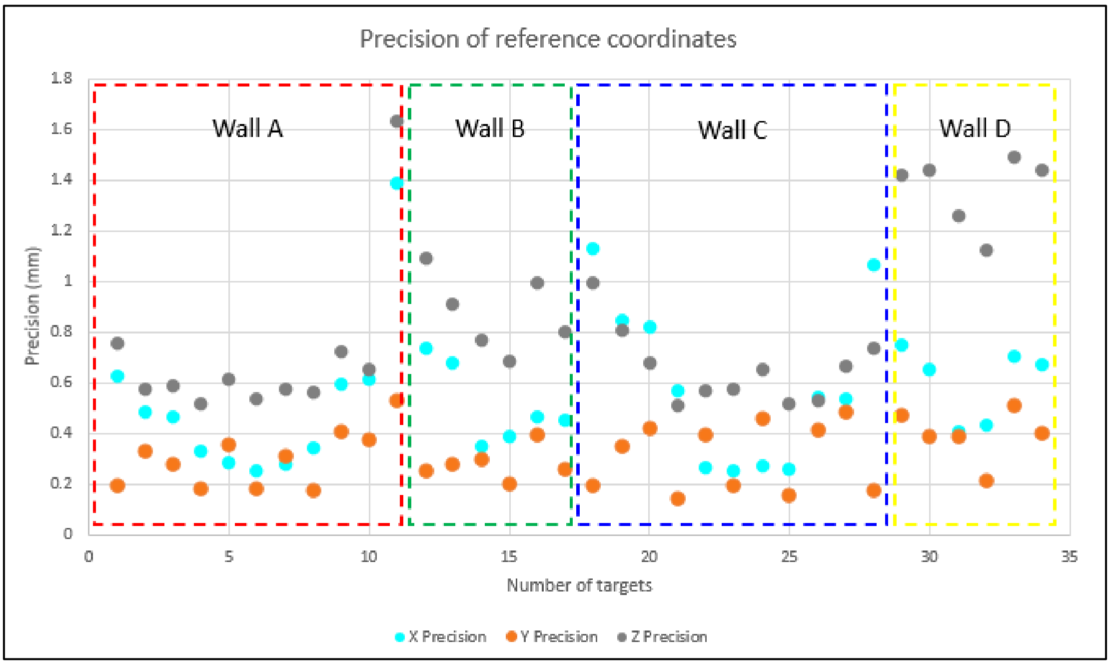


Fig. 4. Precision of reference targets

4.3 Quality Assessment of Reference Calibration Parameters

The initial evaluation of accuracy-oriented approaches involved analysing CPs derived from these methods and comparing them to those obtained using a precision-oriented approach. To ensure the reliability of the CPs derived from the precision-oriented method as reference parameters, thirty (30) independent vectors were generated from both raw and calibrated data (precision-based method). The vectors were compared to true values obtained from the CRP measurement technique, where Figure 5 reveals that the accuracy of the raw TLS data was 5.06 mm. In contrast, the calibrated TLS data, using the precision-oriented method, demonstrated a 60% improvement, achieving a root mean square error (RMSE) of 2.07 mm. This finding is consistent with study by Abbas et al. (2016), which also demonstrated the effectiveness of precision-oriented methods in reducing RMSE. This consistency with existing literature reinforces the conclusion that CPs derived from precision-oriented methods are reliable reference parameters for evaluating the accuracy-oriented approaches.

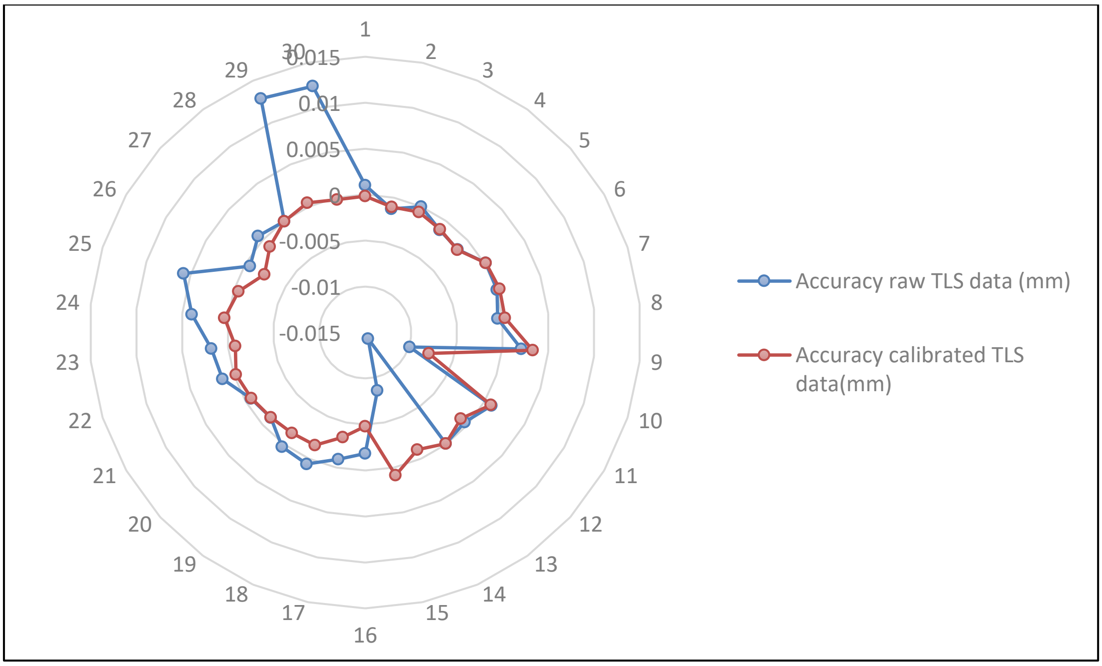


Fig. 5. Accuracies of raw and calibrated TLS data

4.4 Evaluation of Accuracy-Oriented Approaches

4.4.1 Similarity Analysis

The results of the CPs derived from various methods are summarized in Table 2. These CPs, obtained using the proposed techniques, were compared to those from the precision-oriented method via a two-tailed z-test, with a critical value of ±1.96 at a 95% confidence level. As detailed in Table 3, point-based constraint exhibited substantial deviations from the reference CPs, with z-values significantly outside the critical range for constant error (-4.18750), collimation axis error (-16.86047), trunnion axis error (15.73282), and vertical circle index error (-24.71429). Conversely, line-based constraints produced z-values within the ±1.96 range, indicating no significant differences from the reference values for constant error (-0.53125), collimation axis error (0.05426), trunnion axis error (-0.05344), and vertical circle index error (0). To conclude, while point-based methods showed significant deviations from benchmark values, line-based methods aligned closely with them, suggesting higher consistency and accuracy in the latter approach.

Table 2. Derivation of CPs and standard deviations

Calibration parameters	Precision-oriented (mm/")	Accuracy-oriented (mm/")	
		Point-Based	Line-Based
$a_0 \pm \sigma_{a_0}$	14.4 ± 3.2	1.0 ± 0.2	12.7 ± 3.3
$b_0 \pm \sigma_{b_0}$	29.7 ± 12.9	-187.8 ± 57.8	30.4 ± 12.8
$b_1 \pm \sigma_{b_1}$	30.2 ± 13.1	236.3 ± 58.6	29.5 ± 13.0
$c_0 \pm \sigma_{c_0}$	29.9 ± 0.7	12.6 ± 1.5	29.9 ± 0.8

Table 3. Similarity assessment

Calibration parameters	Calculated 'z'	
Accuracy-oriented approaches	Point-based constraint	Line-based constraint
Constant error (a_0)	**-4.18750**	-0.53125
Collimation axis error (b_0)	**-16.86047**	0.05426
Trunnion axis error (b_1)	**15.73282**	-0.05344
Vertical circle index error (c_0)	**-24.71429**	0

Bold-Significant CPs

4.4.2 Accuracy Assessment

After verifying the similarity of CPs to the benchmark, techniques passing this test underwent a significance test to determine the effectiveness of CPs in enhancing TLS measurement quality. Despite the point-based constraint (ASC) method showing statistical differences from benchmarks, their reliability and precision were assessed to ensure method robustness and identify potential improvements.

All CPs were statistically tested using a z-test with a critical value of ±1.645. Table 4 shows that the null hypothesis was rejected for all CPs (a_0, b_0, b_1, c_0) using both point-based and line-based constraint (ASC) methods, indicating a significant influence on scanner observations. Consequently, significant parameters were applied to raw data, resulting in thirty new vectors. Table 5 shows accuracy improvements with precision-oriented, point-based constraint (ASC), and line-based constraint (ASC) methods. The precision-oriented technique achieved 2.07 mm accuracy (from 5.06 mm), line-based constraint (ASC) achieved 1.99 mm, and point-based constraint (ASC) achieved 2.16 mm, highlighting significant accuracy enhancements.

Table 4. Significance of CPs in raw TLS data (with known error)

Calibration parameters	Calculated 'z'	
	Point-based constraint	Line-based constraint
Constant error (a_0)	5	3.848484848
Collimation axis error (b_0)	-3.249134948	2.375
Trunnion axis error (b_1)	4.032423208	2.269230769
Vertical circle index error (c_0)	8.4	37.375

Table 5. Accuracy of different TLS self-calibration techniques

TLS Self-Calibration Techniques	RMSE (mm)
Raw data affected by SE	5.06
Precision-oriented	2.07
Point-based constraint (ASC)	2.16
Line-based constraint (ASC)	1.99

Based on the accuracy assessment, both proposed accuracy-oriented techniques were found to enhance calibration accuracy. Further analysis was conducted to identify the superior solution by examining the standard deviations of the CPs and the residuals. Comparing the two proposed techniques, the line-based constraint (ASC) method provides more stable CPs. As shown in Table 6, it has lower standard deviations: 5.3 mm for a_0, 15.5" for b_0, and 15.8" for b_1. In contrast, the point-based constraint (ASC) method has higher deviations: 0.2 mm for a_0, 57.8" for b_0, and 58.6" for b_1. Additionally, residuals, presented in Table 7, further highlight its superiority, with lower values in the horizontal direction (12.1 mm) and vertical angle (21.5 mm) compared to the point-based constraint

(ASC) method (109.3 mm and 27.2 mm, respectively). This suggests that the line-based constraint (ASC) method is more effective for achieving consistent and accurate TLS calibration.

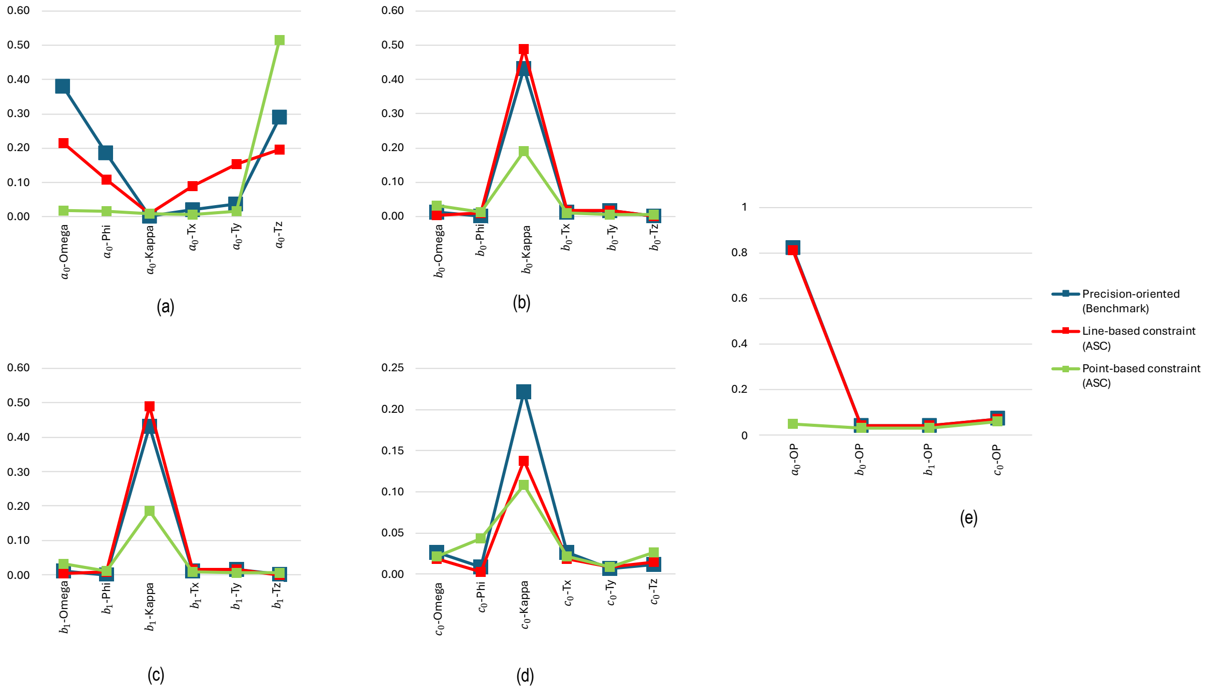
Table 6. Standard deviation

TLS self-calibration techniques	a_0 (mm)	b_0 (")	b_1 (")	c_0 (")
Precision-oriented (Benchmark)	3.2	12.9	13.1	0.7
Line-based constraint (ASC)	5.3	15.5	15.8	1.2
Point-based constraint (ASC)	0.2	57.8	58.6	1.5

Table 7. Residuals

TLS self-calibration techniques	Range	Horizontal direction	Vertical angle
Precision-oriented (Benchmark)	1.3	15.1	19.1
Line-based constraint (ASC)	2.9	12.1	21.5
Point-based constraint (ASC)	1.3	109.3	27.2

The line-based constraint (ASC) method was identified as the most effective based on standard deviations and residuals. To further validate this conclusion, correlation coefficients between CPs were analysed. As suggested by Zhou et al. (2020), this approach addresses potential issues with correlated parameters in point-based TLS self-calibration methods. The correlations were examined in two categories: i) between CPs and EO parameters (Figure 6a-6d) and ii) between CPs and object points (OPs) (Figure 6e).



(a) (b) (c) (d) (e)

Fig. 6. Correlations between TLS self-calibration parameters and exterior orientation: (a) constant error; (b) collimation axis error; (c) trunnion axis error; (d) vertical circle index error; (e) calibration parameters with object points

Overall, the analysis in Figure 6 indicates that both accuracy-oriented methods show weak positive correlations between CPs and the relevant measurements. While the point-based constraint (ASC) method displays the lowest correlation coefficients in most analyses, indicating the minimal impact of CPs on object points and exterior orientations, the line-based constraint (ASC) method demonstrates more consistent weak positive correlations. This suggests that the line-based constraint (ASC) method is more effective overall. Although the line-based constraint (ASC) method exhibits a moderate positive correlation between CPs and OPs, with the highest coefficient of 0.81, as indicated in Figure 6e, it does not attain a perfect correlation $(r = 1)$. This result underscores the effectiveness of Lichti et al. (2011) recommendation to rotate the instrument by 90° at each scanner station, which successfully decorrelates the parameters. This absence of perfect correlation suggests that the method avoids overfitting and potential calibration issues, thereby maintaining a balance between model accuracy and generalizability.

5.0 Conclusion

This study has demonstrated the effectiveness of the line-based constraints (ASC) method in enhancing the quality of TLS measurements, marking a significant contribution to the development of self-calibration techniques. Although the point-based constraint

(ASC) method exhibited weaker correlations among self-calibration techniques, indicating its relative independence from other parameters, it revealed inconsistencies in the parameters derived, pointing to the need for further refinement. These inconsistencies highlight a key limitation of the point-based (ASC) method, suggesting that while independence from other parameters is desirable, it may lead to unreliable calibration outputs.

While the line-based constraints (ASC) method has proven effective in enhancing the quality of TLS measurements, its implementation in this study involves extensive setup, requiring data from 7 scan stations, 27 lines, and 54 targets, making the process time-consuming. This highlights a limitation in scalability, particularly for large-scale projects or field environments where time and resources are constrained. Thus, it is recommended to optimize the network configuration to improve the efficiency by reducing the number of scan stations, lines, and targets, without compromising measurement accuracy.

Building on these recommendations, future research should also explore the development of a dedicated calibration frame for on-site calibration purposes. Although the proposed TLS self-calibration method requires additional data collection to establish reference values, incorporating such a framework would facilitate real-time adjustments and improve measurement accuracy in dynamic environments.

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