DOI: 10.24996/ijs.2023.64.4.43

ISSN: 0067-2904

User Oriented Calibration Method for Stonex X300 Terrestrial Laser Scanner

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Received: 29/6/2022 Accepted: 5/9/2022 Published: 30/4/2023

Abstract

Terrestrial laser scanners (TLSs) are 3D imaging systems that provide the most powerful 3D representation and practical solutions for various applications. Hence this is due to effective range measurements, 3D point cloud reliability, and rapid acquisition performance. Stonex X300 TOF scanner delivered better certainty in far-range than in close-range measurements due to the high noise level inherent within the data delivered from Time of Flight (TOF) scanning sensors. However, if these errors are manipulated properly using a valid calibration model, more accurate products can be obtained even from very close-range measurements. Therefore, to fill this gap, this research presents a user-oriented target-based calibration routine to compute the calibration parameters of Stonex X300 TLS. The proposed routine investigates range and angular measurements to mitigate mechanical misalignment error sources of this device.

Distance and angular index errors were computed, and environmental error sources were considered for optimal modeling estimation. The approach is based to reference measurements in a close-range environment within a 10-meter distance to user-defined ground truth targets. Experiment results show that the errors in the distance are generally increased following the increase in range distance between the laser device and the targets. However, error variations between laser and reference measurements nearly constant relational to the range value. The index error of the Stonex X300 was computed based on mean measurements and found to be equal to 4.6717 mm.

On the other hand, the horizontal angular measurements delivered from the TLS device were found to be more consistent with the reference measurements than with thee vertical angular measurements. However, the vertical angular measurements show more significant variations in particular measures compared to horizontal angular measurements. Following this, the angular error index was computed and found to be equal to 0.07 seconds and 0.13 seconds in horizontal and vertical angular measurements, respectively.

Keywords: Remote Sensing, Terrestrial laser scanning, calibration, error modeling, performance evaluation, error analysis.

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معايرة جهاز الماسح الليزري الارضي *Stonex X300* باستخدام طريقة موجهة من قبل المستخدم

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الخلاصة

ان اجهزة المسح الليزري الارضية والتي تسمى اختصارا بالـ (TLS) هي أنظمة تصوير ليزرية توفر بيانات ثلاثية الأبعاد وتُستخدم لتقديم أقوى تمثيل مجسم للعوارض الارضية عبر تقديم حلول عملية تحاكي الواقع في مختلف التطبيقات العلمية عموما والهندسية خصوصا. يمكن استخدام هذه الاجهزة في المشاريع الكبيرة والصغيرة على حد سواء حيث يمكن من خلالها الحصول على تمثيل ثلاثي الابعاد للمعالم الارضية بدقة عالية جدا تتراوح بين بضع سنتمترات الى بضع مليمترات. يعتبر جهاز Stonex X300 أحد أجهزة الـ TLS الحديثة والذي اثبت كفاءته في المجال التطبيقي مؤخرا. الجهاز يعمل بنظام ألـ TOF والتي تتميز بقدرتها على تقديم بيانات افضل في المشاريع التي تعتمد على قياسات بعيدة المدى مما هو في البيانات القريبة جدا وذلك بسبب المستوى العالي للضوضاء الكامنة في البيانات المقدمة من القياسات القريبة من مستشعرات النظام. لكن على الرغم من ذلك يمكن معالجة الاخطاء الناتجة من هذه القياسات اذا ما تم استخدام اسلوب معايرة مناسب للاخطاء المستحصلة والناتجة عن عدم تطابق القياسات الزاوية والخطية المحسوبة من البيانات المرصودة من الجهاز. عندها يمكن الحصول على منتجات أكثر دقة حتى من القياسات القريبة جدًا. لذلك ولسد هذه الفجوة ، يقدم هذا البحث نموذج معايرة لجهاز Stonex X300 TLS قائم على موديل تطبيقي موجه من قبل المستخدم لحساب معاملات المعايرة للجهاز. يقوم روتين المعايرة المقترح بالتحقيق في القياسات الخطية والزاوية للتخفيف من مصادر خطأ المحاذاة الميكانيكية لهذا الجهاز من أجل تقييمات مراقبة الجودة المستقبلية لمشاريع المستخدم النهائي. تم حساب خطأ مؤشر المسافة وخطأ المؤشر الزاوي بالإضافة إلى مصادر خطأ المقياس البيئي التي تأخذ في الاعتبار تقدير النمذجة الأمثل للهدف قيد الدراسة. يعتمد النهج على القياسات المرجعية في بيئة قريبة المدى في نطاق مسافة 10 أمتار باستخدام اهداف ارضية حقيقية يحددها المستخدم. أضهرت نتائج التجربة أن الأخطاء في المسافة تزداد بشكل عام بازدياد المسافة بين جهاز الليزر والهدف المرصود. ومع ذلك، كان اختلاف الخطأ بين قياسات الليزر والقياسات المرجعية ثابتًا تقريبًا لجميع المسافات قيد التطبيق. تم حساب ثابت الجهاز بناءً على القياسات المتوسطة ووجد أنه يساوي 4.6717 ملم. من ناحية أخرى، وجد ان القياسات الزاوية الأفقية التي تم احتسابها تكون أكثر اتساقًا مع القياس المرجعي مقارنة بالقياسات الزاوية الرأسية. حيث تُظهر القياسات الزاوية الرأسية اختلافات أكبر في قياسات معينة مقارنة بالقياسات الزاوية الأفقية. بعد ذلك، تم حساب مؤشر الخطأ الزاوي ووجد أنه يساوي ″0.07 و ″0.13 في القياسات الزاوية الأفقية والرأسية على التوالي.

1. Introduction

Laser scanner companies used to publish the accuracy standards for the public to demonstrate the potential of the devices for different applications. However, following practical experiences from end users, these standards tend to vary in different devices and various case studies due to multi variables [1][2][3]. Therefore, individual calibration scenarios are highly recommended when accuracy is the main concern in a particular applications [4][5]. Stonex X300 is a pulsed mid-range TOF terrestrial laser scanner (TLS) device that shows the potential to deliver accurate range measurements in mid and close-range applications [6] [7]. However, close-range measurements from this device counter instability in precision measures due to the accumulated level of noise delivered from measurements referenced to multiple effects such as the incidence angle of a laser beam, weak laser returns, limitations in signal post-processing returns, and range-finder precision capabilities [8][9]. Therefore, there is a need for further investigations to study the behavior of these measurements following a proper calibration routine to apply an adequate analysis pipeline to overcome limitations in close-range applications.

Available TLS calibration strategies are generally based on the type of the scanned objects used to estimate the calibration parameters [10]. Studies proved to eliminate errors in range measurements following these strategies and improve data reliability to a certain level [11]. However, measurement uncertainty mainly depends on the algorithm applied and the investigated device type [5][12]. The strategies can be classified into two groups: prior data acquisition (target-based) approaches and post-data acquisition and measurements (in-situ) approaches [13] [14]. The first group is called self-calibration, a target-based approach delivered from too many target measurements to guarantee the quality of the pre-defined targets' centers and thus increase the precision reliability of the calibration process [1]. However, this approach lacks efficiency as it requires hundreds of targets for multiple scans acquired from multiple directions. Therefore, it is a labor-intensive calibration approach which mainly affected by optimizing the target network design and the efficiency of the target field of the TLS device. On the contrary, in-situ calibration approaches are more efficient than self-calibration as they provide up-to-date solutions using configured measurements based on shapes found in the calibration scene [15]. However, these approaches mainly depend on estimating the target geometrical primitives and therefore require best-fit algorithms to estimate proper and accurate calibration parameters.

2. Review of Relevant Literature

To obtain precise and high-quality measurement results, calibrating range-based devices such as TLS is becoming essential due to the systematic influence of instrumental errors obtained from misalignment and falsification of the measurements delivered from sensors [16]. In order to minimize the influence of errors, a calibration routine should not be underestimated by using a specific calibration assumption to deliver the best estimation of the calibration parameters. In this respect, several studies discuss calibrating TLS data measurements following self-calibration and in-situ routines. Regarding the conception of TLS sensors, [2] presented a modified spherical-based calibration approach by adjusting planes to estimate calibration parameters using a developed prototype laser scanner device in TU Berlin. Following variance component approximation, the precision level of the calibration parameters is computed and analyzed, representing the quality of the individual laser device components. Later, [17] presented a self-calibration model to improve parametric modeling of the unknown systematic errors of panoramic and hybrid TLS devices following the quality index approach. Different systems are investigated, including TOF and Phase-shift continuous, to determine the best additional calibration parameters through analyzing systematic errors in distance and range measurements. In the same respect, [15] introduced an up-to-date self-calibration review based on calibration point field assumption, which discussed how calibration models could be influenced by device specifications and reviewed available experiments and errors obtained following instrumental component imperfection. They found that for each TLS device, a calibration model should be set as an approximation to the total station model and improved through a calibration point field environment to approach the optimal parametric values. However, developing the optimal calibration model is not yet available, and therefore more experiments and studies need to be established for better findings.

On the other hand, [13] revealed a self-calibration approach based on a user-oriented scenario to measure the angular error in TLS sensors. They used the ray-tracing method in a lab-built experiment to model angle increment in laser measurements. Following this modeling, the researchers successfully eliminated errors in horizontal and vertical angle measurements. However, errors acquired from mirror tilt and vertical index offset are challenging to manipulate and highlighted as the primary error sources of laser measure misalignment. At the same time, they found that the errors from standing tilt and laser beam tilt are considered to have a minor effect when adjusting model parameters. Later, a point-based self-calibration method of TLS measurements was proposed by [14]. The method used a posterior estimation of the unknown calibration parameters to deliver more realistic modeling parameters relative to true accuracy than to nominal accuracy. Following this assumption, they managed to deliver effective improvements by reducing errors compared to those delivered from traditional self-calibration models to approach the corrected coordinates. They analyze distance and angle measurements in the proposed estimation approach, which shows potential for the computed calibration parameters. Recently, [18] used network stationary targets to improve laser measurements through a practical calibration routine towards improving the accuracy of TLS measurements. They introduced two methods to measure the lab targets from different directions; once using a laser tracker (LT) and once using the TLS device itself. They found that both methods work fine to estimate calibration parameters; thus, there is no need to use a higher accuracy reference device to calibrate TLS measurements and evaluate performance.

Following previous studies, in this research, a user-oriented calibration approach was adopted to maintain up-to-date estimation of Stonex X300 calibration parameters and characterize the relevant misalignment in laser measurements that could significantly affect accuracy in precise close-range measurements.

3. Stonex X300 Laser Scanner

Stonex X300 (Figure 1) is been considered a brand new TLS device in the laser scanning commercial sector since 2006. It designed to provide accurate measurements in 3D space in a short period of time using laser light within near-infrared wavelength [19]. It is a compact and lightweight Terrestrial laser scanner that works in a 3D environment and delivers direct 3D measurements. It is based on a time of flight (TOF) laser ranging system and consists of a laser range finder integrated with the transmitted deflection unit to transmit the light towards objects and reflect light to the receiver within a specific period of time. The laser range finder of this device finds the distance to the Earth's object by recording the time of the round-trip of the transmitted and the reflected light echoes [20]. Infrared laser light emits the laser beam to record the travel time between the laser sensor and the object using a system detector [21].

Since the speed of light c is known, the round-trip time is computed, and the range can be estimated following the speed of light formula (Eq. 1) [16].

$$R = c * \frac{t}{2} \tag{1}$$

Where R represents the range between the object and the device sensor, c represents the speed of light, and t is the round-trip time.

The accuracy of the registered time measures depends on how precisely the time is measured based on the device components [20]. The device proved its reliability and flexibility as a competitive, accurate laser device in different projects in close-range environments. This includes Building Information Modelling (BIM), as-built scan infrastructures, volume calculations in engineering surveying works, scanning architecture facades and interior monumental objects, and many other projects [22][23][24].

Stonex X300 can be provided with optional accessories to improve measurement performance, see Figure 1. These include 1) monitoring and GPS kit, which provides an external power supply and Ethernet cable for monitoring projects in addition to GNSS receiver accessories to georeferenced the 3D measurements after connecting the appropriate GNSS device to the X300 device; 2) X300 Framework kit to scan building ceilings and all features tilted 90° from horizon; 3) the camera kit which utilized for integrating photogrammetry to laser data by installing a DSLR camera to the device body to increase image quality and resolution [19].

Figure 1: Stonex X300 TLS device with accessories: (Left) Stonex X300 3D laser scanner Device (Right) Stonex X300 accessories including monitoring and GPS kit, Framework, and Camera kit.

4. Calibration Approach

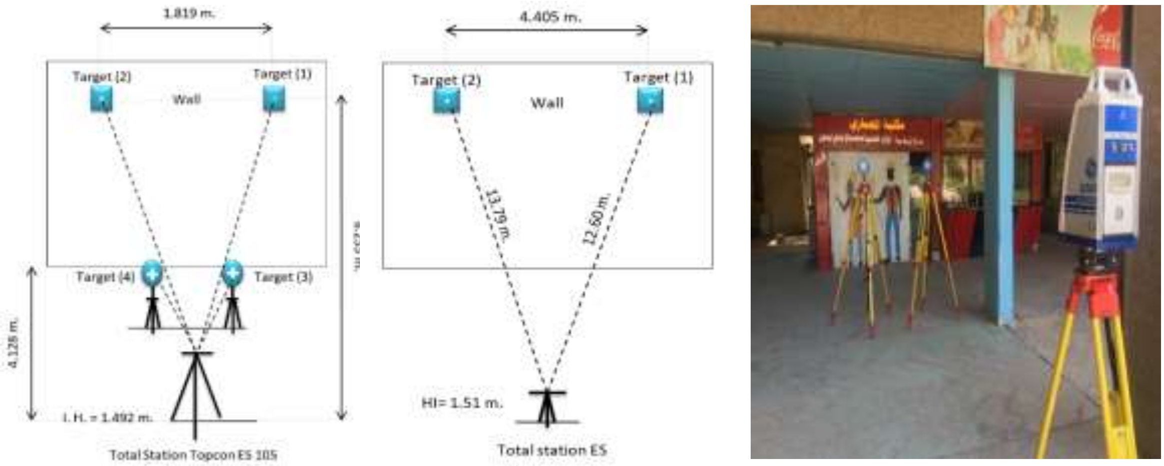
In this research, the calibration routine is based on the recent new X300 Stonex laser scanner. The technical performance specifications of this 3D laser scanner are highlighted in Table 1. It can be seen from Table 1 that the range accuracy level in the device is below 6 mm at 50m distance, which is based on laboratory tests. However, a practical investigation is needed to check the accuracy level in shorter ranges. In order to investigate the accuracy of Stonex X300 range measurements, there is a priority to calibrate the device range finder according to a relative reference device. Therefore, a user-oriented calibration routine was adopted by estimating distance (index error), angle (signal wave error), and environment scale errors compared to reference measurements. The reference device was selected to be Topcon ES-105 total station (www.topconpositioning.com) to measure the range, angle, and environmental index errors of Stonex X300 laser scanner measurements.

Table 1: Technical Performance Parameters of Stonex X300 3D Laser Scanner (http://www.stonex.it).

Parameter	Setting
Range	1.6-300 m.
Scan Rate	Up to 40,000 pt./sec.
FOV	Horizontal: 360° Vertical: 90°
Beam Diverge	0.37 mrad.
Angular Resolution	Horizontal: 1.35′ Vertical: 1.35′
Density	39×39 mm. @100 m.
Range Accuracy	< 6mm. @ 50m. < 40 mm. @ 300m.
Laser Wavelength	905 nm. (Visible)
Resolution	1944×2592×2 px.

Two calibration sets are adapted to include the most systematic error types in laser measurements. The first set was applied by setting the total station device at 8.255m and at 4.128m far from two groups of reference targets respectively and measuring ranges, horizontal angles, and vertical angles to four different targets with different setting configurations, as illustrated in Figure 2 (a). The second observation set was applied on another day with cloudy, cold weather to consider environmental conditions. The setting in the second set was slightly different from the first set as only two targets were used, and the total station device was set farther from the targets as applied in the first set. The ranges between the targets were also changed to consider different linear and angular measurements, see Figure 2 (b). The second set was also applied to double-check the calibration process and ensure that whether using a different setting configuration is confident enough to deliver the same reliable conclusions. It is essential to mention that the two measurement sets were repeated individually using two ES-series total station devices as a reference to consider instrument error and deliver more confidence zero measure reference values. This was obtained by comparing measurements from both devices and selecting the most confident and stable device to be considered as a reference in later analysis.

Every target center was observed in an individual measure set five times, and the measurements were recorded and exported later for statistical analysis. This process was later re-applied using the Stonex X300 device, which was set with care using the exact configuration of the reference device, including positioning, centering, leveling, and device height. Then, the ground targets are scanned in five sets of observations and later post-processed to deliver the approximate center point of individual targets to compute accurate distance values between the scanner center point and target points, see Figure 2 (c).



a b c

Figure 2: Calibration Settings Overlay: (a) Total Station first setting (b) Total Station second setting (c) Stonex X300 settings.

In order to compute the index error of the scanner device, which defines the difference between the measured and the reference zero measure delivered from the total station device, the following formula was applied:

$$TS_1 + TS_2 = (S_1 + I) + (S_2 + I) \quad (2)$$

Where: TS1 and TS2 represent the mean total station range measurements delivered from the left and right targets in Figure 2.
S1 and S2 represent the mean computed scanned distances measured by the laser device, while I represents the index error targeted for computation. By re-arranging Eq. 2, the index range error can be delivered as follows:

$$I = (TS - S)/2 \quad (3)$$

However, errors encountered due to scale differences following different range measurements were computed as follows:

$$TS_{1+2} = S_{1+2} * S_c \quad (4)$$

Thus:

$$S_C = TS_{1+2}/S_{1+2} \quad (5)$$

Where: Sc is representing scale error is the Stonex X300 device.

TS1+2 and S1+2 represent the mean range values of the left and the right targets delivered from the total station and laser devices.

As for the angular errors acquired due to measurements differences in the incident angle of the laser beam signal, it was estimated following the cosine rule using measured horizontal distances from both total stations measurements and Stonex X300 laser scanner and as follows:

$$\cos A = \frac{b^2+c^2-a^2}{2bc} \quad (6)$$

$$\cos B = \frac{a^2+c^2-b^2}{2ac} \quad (7)$$

$$\cos C = \frac{a^2+b^2-c^2}{2ab} \quad (8)$$

Where A, B, and C represent triangle vertices used to compute triangle angles in the cosine rule, while a, b, and c represent triangle sides connecting vertices. They reflect measurements between every adjacent measured target in Figure 2 (e.g., targets 1 and 2) and the device sensor. Later, differences have been computed between angular measurements from the total station/s and the scanner device.

5. Results Analysis and Discussion

As the geometric quality of the 3D point cloud is a priority in any TLS project, the accuracy cannot be guaranteed without applying an individual calibration scheme to detect systematic and random errors inherent within measurements delivered from the TLS device. The errors could be instrumental, method-related, environmental, and object-related error types. Index error computations based on target measurements delivered from implemented calibration approach were analyzed to compute the index range error in Stonex X300 laser scanner device. Figure 3 illustrates set 1 measurement following calibration setting configuration represented in Figure 2 (a) to show the mean error behavior of Stonex X300 measurements compared to reference zero measurements delivered from the ES device.

It is evident that the overall number of errors increases whenever the range increases. This is clear from the error values delivered from target 1 and 2 measurements compared to errors delivered from target 3 and 4 measurements as the latter targets have been set about half the way far from the laser device than target 1 and 2 sets, see Figure 2 (a). However, error variation between laser and reference measurements is apparent and nearly constantly relational to the range value. Considering all measurement sets delivered from the reference device, the index error of the Stonex X300 was computed, following Eq. 2, to be 4.6717 mm.
The index value defines the relation between the mean laser range measurements of the Stonex X300 device and the actual mean zero measurements of the ES device. However, 4.8565 mm was the index error computed following measurements delivered based on the second ES reference device. From the delivered errors, it was clear that the setting configurations were accurate enough to be considered; however, differences still exist due to environmental conditions that could also affect the scale and angular measurements.

Figure 3: Compared with reference target measurements, the mean range errors of Stonex X300 were delivered from calibration targets (set 1).

The calculation was based on the measurement set following settings illustrated in Figure 2 (a) to compute scale error in the laser device. The distances between the left targets (2 and 4) and the right targets (1 and 3) were the base measures to compute the scale error in the applied calibration routine. Therefore, the distances are computed carefully based on mean range measurements delivered from laser devices compared to reference devices. Table 2 illustrates the measures and highlights computed differences that lead to the scale error in Stonex X300 range measurements.

The scale error values show a consistent outcome from both reference devices. However, slight differences are still acquired, which might be due to user errors or environmental conditions, as the second measurement set was observed in cold weather conditions during winter 2019.

Table 2: Scale Index Error of Stonex X300 based on calibration targets (set 1) measurements.

	Distance Target To Target	ES Range m.	Stonex X-300 Range m.	Diff. m	Scale Error
TS I	2 to 4	4.04181	4.04803	0.00622	1.000295
	1 to 3	3.98266	3.97407	0.00859	
TS II	2 to 4	4.04192	4.04804	0.00612	1.000300
	1 to 3	3.98259	3.97406	0.00853	

As for angle error analysis, both vertical and horizontal angular measurements are considered. In ES, these angles were observed for individual targets, just like the range measurements used to compute the index and the scale errors. However, in the Stonex X300 device, the values are computed from point cloud coordinates based on the cosine Law formula following Eq. (6-8). Figure 4 and Figure 5 show the analysis of the angular measure in seconds for both horizontal and vertical angles based on observation set 2, following configuration settings illustrated in Figure 2 (b).

It can be seen from these figures that angular measure behaves a bit differently from range measures, and more different errors are delivered from angular measures. This can be targeted through error values delivered from vertical and horizontal angles in target 1 and 2 measurements. However, it is obvious that the horizontal angular values computed from the Stonex X300 device are more consistent with the reference measurements than vertical angular measurements in both targets. It can also be noticed that the vertical angular measures deliver more significant variations in particular measures, whereas these errors could be considered outliers due to the observer's erroneous measure. However, the errors did not affect the mean values as differences were still insignificant. Following information delivered, angular error index can be estimated following the same concept applied when computing scale error index found to be 0.07 and 0.13 seconds in horizontal and vertical angular measurements, respectively.

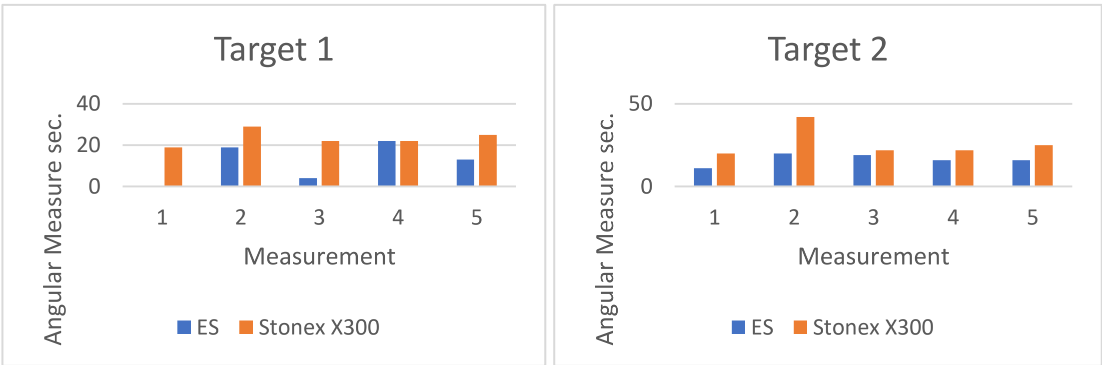


Figure 4: Mean vertical angular errors of Stonex X300 delivered from calibration targets (set 2) measurements compared with reference target measurements.

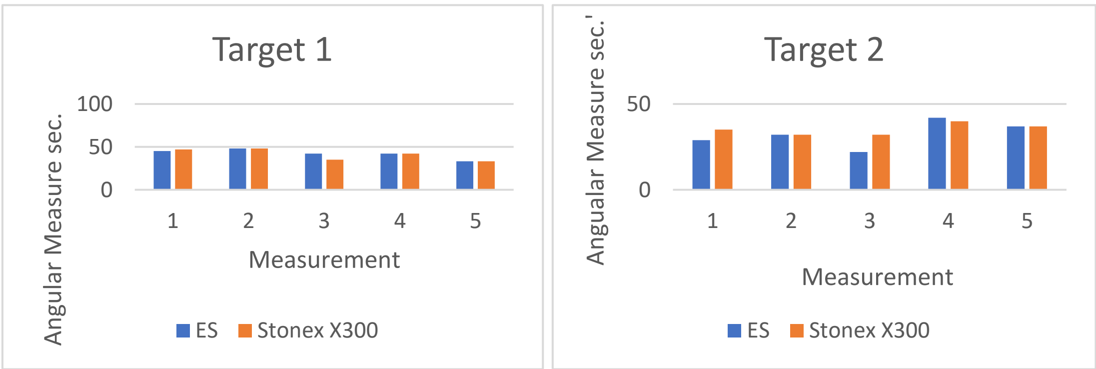


Figure 5: Compared with reference target measurements, the mean horizontal angular errors of Stonex X300 were delivered from calibration targets (set 2) measurements.

6. Conclusions

All terrestrial laser scanner (TLS) measurements are affected by systematic instrumental error sources and therefore should be manipulated to ensure high-quality measurement accuracy. The errors are caused by unavoidable mechanical misalignment in device components and should be treated mathematically prior to or posterior to physical measurements. Calibrating the devices to mitigate the error sources is a priority for accurate measurements, especially in close-range indoor measurements where error effects become highly tangible. This research presented a user-oriented calibration application on the brand new Stonex X300 TLS device in a close-range environment to compute the calibration parameters of the device.

The approach focuses on estimating distance (index error), angle (signal wave error), and environment scale errors compared to reference measurements, which were selected as Topcon ES-105 total station to measure range, angle, and environmental index errors of Stonex X300 laser scanner measurements. Two calibration sets are adopted to include most systematic errors in laser measurements at less than the 10 m range. Results revealed that the overall distance errors increase whenever the range between the device and the scanned target increases. Scale error was computed by considering mean range measurements computed from laser devices compared to reference devices. However, error variation between laser and reference measurements was nearly constant relational to the range value. The index error of the Stonex X300 was found to be equal to 4.6717 mm.

Conversely, angular results analysis showed that the horizontal angular values computed from the laser device were more consistent with the reference measurement than with the vertical angular measurements. The vertical angular measurements showed more significant variations in particular measures compared to horizontal angular measurements. However, the errors did not affect the mean values as differences were still insignificant. In horizontal and vertical angular measurements, the angular error index was computed in seconds equal to 0.07 seconds and 0.13 seconds. All the calibration parameters should be considered when using the Stonex X300 device and measurements for quality assurance by end-users in the commercial sector.

7. Conflict of Interest

The authors declare that they have no conflicts of interest.

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