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Article

Terrestrial Laser Scanners Datum Transformation: Insignificant Analysis of Scale Factor

Mohd Azwan Abbas[1,2,a,*], **Zulkepli Majid**[3,b], **Mohamad Aizat Asyraff Mohamad Azmi**[2,c], **Albert K. Chong**[4,d], **Mohamad Asrul Mustafar**[2,e], **Lau Chong Luh**[3,f], **and Anuar Aspuri**[3,g]

1 Faculty of Architecture, Planning & Surveying, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia
2 Centre of Studies for Surveying Science & Geomatics, Universiti Teknologi MARA Perlis Branch, Arau Campus, 02600 Arau, Perlis, Malaysia
3 Faculty of Built Environment & Surveying, Universiti Teknologi Malaysia, 81310 Skudai, Malaysia
4 School of Civil Engineering & Surveying, University of Southern Queensland, Australia
E-mail: [a]mohdazwan@uitm.edu.my (Corresponding author), [b]zulkeplimajid@utm.my, [c]sraizatazmi@gmail.com, [d]albertkon-fook.chong@usq.edu.au, [e]mohamadasrul@uitm.edu.my, [f]lauchongluh@gmail.com, [g]anuaraspuri@gmail.com

Abstract. Due to the measurement mechanism employed by terrestrial laser scanners (TLSs), the pre-processing procedure has become crucial procedure to orient all acquired data into global or ground coordinate system. Rather than utilising all seven-transformation parameters, most of TLS practitioners have neglected the scale factor. Taking into consideration the uncertainties in deriving range data, disregarding the scale factor in datum transformation computation could jeopardise the quality of pre-processed results. To rigorously examine this argument, two experiments have been designed by considering the element of multi distances and multi sensors. Utilising phase (i.e. Faro Focus 3D) and pulse-based (i.e. Leica ScanStation C10) scanners, both experiments were carried out with computation of seven (7) transformation parameters and scale factors were extracted for the assessment. With the aid of statistical analysis, the computed scale factors were mathematically differentiate to the ideal value (i.e. 1.000 or no scale effect). Under 95% confidence level, the null hypotheses for both experiments have indicate an agreement that scale factor can be neglected in datum transformation process for both types of terrestrial laser scanners.

Keywords: Terrestrial laser scanner, datum transformation, scale factor, network configuration, significant analysis.

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1. Introduction

Capability to provide rapid and dense three-dimensional (3D) data have made terrestrial laser scanners (TLSs) widely employed in various of implementations including application that demand high accuracy information (e.g. sub-centimetre). Among those applications are structure health assessment [1], fracture detection [2], structural deformation measurements [3]-[4], stability analysis for hazardous natural features [5], slope monitoring [6] and industrial measurements [7]-[8]. However, uncertainty is unavoidable factor in almost all measurement sensors, thus, further investigations are mandatory to ensure the quality of the acquired data. Similar principle is applied in terrestrial laser scanners (TLSs) measurement where errors can be augmented not only limited to data acquisition phase but also in processing procedures. According to Genechten [9], TLSs data processing can be categorised into two phases: i) Pre-processing; and ii) Post-processing. In most situations, it is impossible to scan a complete three-dimensional (3D) surfaces of the object from single occupied station (as illustrated in Fig. 1). Therefore, multiple scanning positions are inevitable. Due to the mechanism employed by TLSs which local coordinate system will be established in every scan stations, then a procedure to align different scan positions is necessary. This aligning process also known as registration used to identify the exact position and orientation of all scanner coordinate systems with respect to one common (e.g. global) coordinate system. For mapping or database purposes, all data have to be georeferenced or transformed to the ground coordinate system. This may be either national or local coordinate system. To complete pre-processing phase, TLSs data are optionally need to be reformatted to enable for further processing. Post-processing phase is highly dependent on the customer needs, final products can be two-dimensional (2D) plan, 3D Computer Aided Design (CAD), solid, photo-realistic or meshed model.

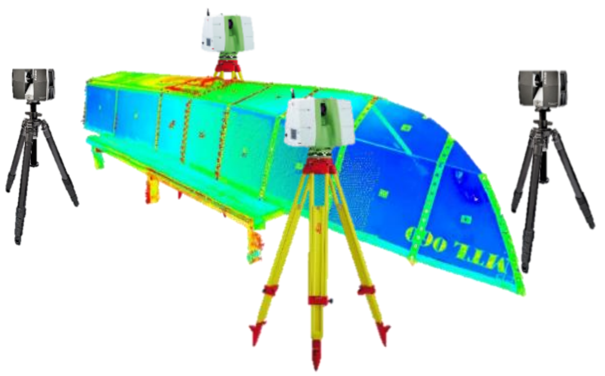

Fig. 1. Four (4) scanner positions required to scan a complete 3D surfaces of the object.

Uncertainties in TLSs measurement have been extensively investigated and most researchers continue to explore some possibilities for simplifying and enhancing existing implementations and results [10]-[13]. Conversely, very few research carried out have been associated to uncertainties in TLSs processing. The errors yielded in the post-processing phase are substantially uncertain and standardise the investigation is impossible due to the reliance on the algorithm employed. In contrast, both pre-processing procedures, registration and georeferencing utilised similar algorithm known as rigid-body-transformation to obtained seven parameters (i.e. 3 rotations, 3 translations and a scale factor). Nonetheless, Gordon and Lichti [14] did mention that the scale factor has shown to be irrelevant in TLSs datum transformation procedure. Therefore, only six (6) parameters (without scale factor) were utilised as follows: i) Translation in three-dimensional axes (Δ_X, Δ_Y, Δ_Z); and ii) Rotation around the three-dimensional axes (ω, φ, $\varkappa$).

Able to acquire dense 3D points with rapid and quality measurement, TLSs have become an option for various implementation, including spatial documentation, investigation, preservation and decision-making. For that reason, further investigation regarding any possibilities that can complicate the quality of TLSs data is crucial. In TLSs pre-processing phase, Rueger [15] has expressed regarding numerous of error sources that can contribute for scale uncertainties. Instrument or internal error sources can be considered as the common causes that can decrease the quality of TLSs measurement, however, mechanism employed to perform non-contact measurement and dependency on algorithm has made external influences also significant. With regard to scale errors, among external effects that can reduce the quality of pre-processing results are weak network configuration utilised to derive transformation parameters [16], less point clouds precision to determine target centroid [17] and form fitting algorithm has wrongly determine the shape of the object [18]. Furthermore, limitation of TLSs georeferencing procedure that require assistance from other measurement approaches to establish known coordinates also need further investigation. Differ mechanism employ by other measurement sensors to acquire three-dimensional data will definitely contribute to scale error when orienting various measurement into single coordinate system. Those arguments have demonstrated that it is questionable to disregarding the scale factor, particularly in applications that require high accuracy measurement. Further research is crucial to concretely examine that scale factor is negligible in TLSs pre-processing phase. To scrutinise this issue, this study has quantitatively evaluate the significant of scale factor using Faro Focus 3D (phase-based) and Leica ScanStation C10 (time-of-flight) scanners. Two kinds of experiments have been designed to ensure that each pre-processing phase were robustly examined. Outcomes from multi distances (for registration experiment) and multi sensors (for georeferenced experiment) were statistically analyse to arithmetically verify the results obtained.

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2. Terrestrial Laser Scanner Pre-Processing

Due to the TLSs mechanism which established local coordinates system for each occupied station, thus, orienting into single global coordinate system (known as registration) is crucial. To ensure that TLSs registered data are applicable for geospatial purposes, later phase of pre-processing will be exploited to transform from scanner into appropriate ground coordinate system (georeferenced). Since the algorithm employed to compute seven (7) parameters for both pre-processing phases are similar [11], hence, arithmetical discussion on seven-parameter similarity transformation were made using registration example.

As illustrated in Fig. 2, this circumstance presumed that the registration procedure was carried out using two (2) scanner positions. Local coordinates system for both scanners are as follow: i) Reference station (X_i, Y_i, Z_i); and ii) Subsidiary station (x_i, y_i, z_i). With the aid of resection technique, all transformation parameters were computed from minimum of three (3) common targets. To ensure the quality of derive parameters, those targets acquired by both scanner positions (e.g. reference and subsidiary stations) must be well-distributed.

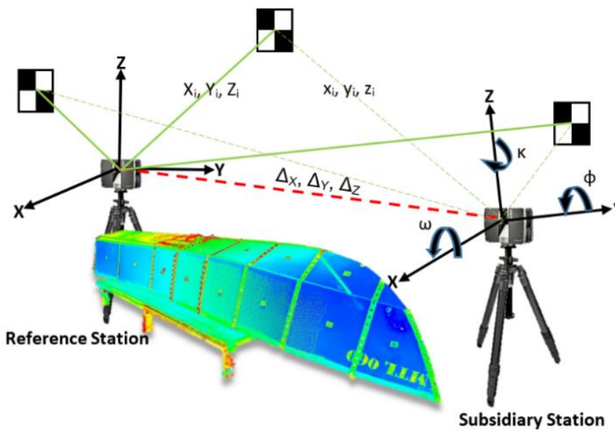

Fig. 2. Registration of two (2) scanner positions.

According to the rigid-body transformation, relation of pairwise scanner positions can be derived using the equations as follows [19]:

$$X_i = T + S.R.x_i \quad (1)$$

where:

X_i = Coordinates of the i[th] target in the reference scanner coordinate system.
S = Scale factor.
R = Rotation matrix.
x_i = Coordinates of the i[th] target in the subsidiary coordinate system.
T = Translations in three-dimensional axes.

Regardless the scale factor in TLSs pre-processing procedure as stated by Gordon and Lichti [14], there are only six (6) parameters were utilised to correlate between pairwise coordinate systems. Neglecting the scale element, similarity transformations are as follows:

$$X_i = T + R.x_i \quad (2)$$

Due to the aim of this study is to examine the significance of scale factor in TLSs pre-processing procedures, thus, Eq. 1 has been employed.

3. Experiments

Two experiments were carried out in this investigation, which concentrated on the examination of scale factor significant in multi-distances and multi-sensors implementation. As mentioned earlier, determination of the study is to ensure that uncertainty in TLSs pre-processing procedure can be reduced, hence, multi-distances experiment will benefit for the registration phase while multi-sensors for georeferenced.

3.1. Multi Distances

Taking into account the robustness of terrestrial laser scanners measurement with regard to various ranges of data acquisition, calibration field has been established at Faculty of Built Environment and Surveying, Universiti Teknologi Malaysia, Malaysia. As illustrated in Fig. 3, there are six (6) points with homogenous interval (i.e. 10m) were marked at the calibration field. To ensure that acquired data can be quantitatively registered, four (4) checkerboard and two (2) sphere targets have been well distributed. Both Faro Focus 3D (phase-based) and Leica ScanStation C10 (pulse-based) scanners were positioned at every mark to scan all six (6) targets (as depicted in Fig. 4(a) and Fig. 4(b)).

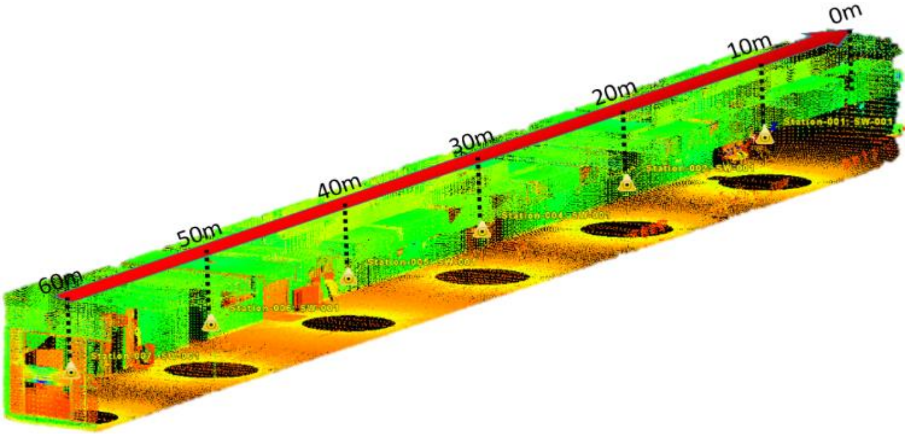

Fig. 3. Calibration field with six (6) range variants.

(a)

(b)

Fig. 4. Multi-distances experiment for Faro Focus 3D (a) and Leica ScanStation C10 (b) scanners.

With consideration that the scanner position with range of 10m from targets will contribute minimum errors (e.g. derivation of distance and resolution of point clouds to determine target centroid), thus, this point has been selected as registration reference (i.e. 10m) for other scanner positions (i.e. 20m, 30m, 40m, 50m and 60m). This configuration has result five (5) registration pairs obtained for multi-distances experiment. To quantitatively prove the significant of scale element in TLSs registration phase, statistical analysis has been utilised to arithmetically differ the computed scale factor to ideal value (i.e. 1.000).

3.2. Multi Sensors

Requirement of control points established in national coordinate system has demanded the assistance of others appropriate measurement approaches in TLSs georeferencing procedure. In this study, global navigation satellite system (GNSS) and total station were exploited in order to prepare six (6) georeference points (blue triangle marks in Fig. 5). The investigation site was located at Universiti Teknologi Malaysia, Malaysia along the road with length 500m (Fig. 5). GNSS observation was carried out using static method at two (2) points (red diamonds in Fig. 5) to establish ground coordinates at experiment site. Propagation of position from GNSS points to the six (6) georeference points were performed using traversing method. To yield adjusted coordinates for each georeferencing points, least square adjustment is utilised (using STAR*NET software) with precision setting of 5", 10" and 7mm for horizontal angles, zenith angles and distances, respectively.

With the establishment of georeference points at site, experiment was continue with data acquisition using phase based (Faro Focus 3D as illustrated in Fig. 6(a)) and pulse based (Leica ScanStatin C10 as depicted in Fig. 6(b)) scanners. Due to the limitation of measurement mechanism imposed by phase-based scanner which was only capable for middle range measurement (e.g. 130m), thus, five (5) scanner positions were required to measure all six (6) georeference points (Fig. 5). In contrast, pulse-based scanner or also known as long range scanner able to measure up to more than a kilometre, however, for this study Leica ScanStation C10 only can goes until 300m. This advantage has made pulse-based scanner only exploited three (3) scan stations to cover all georeferencing points (Fig. 5).

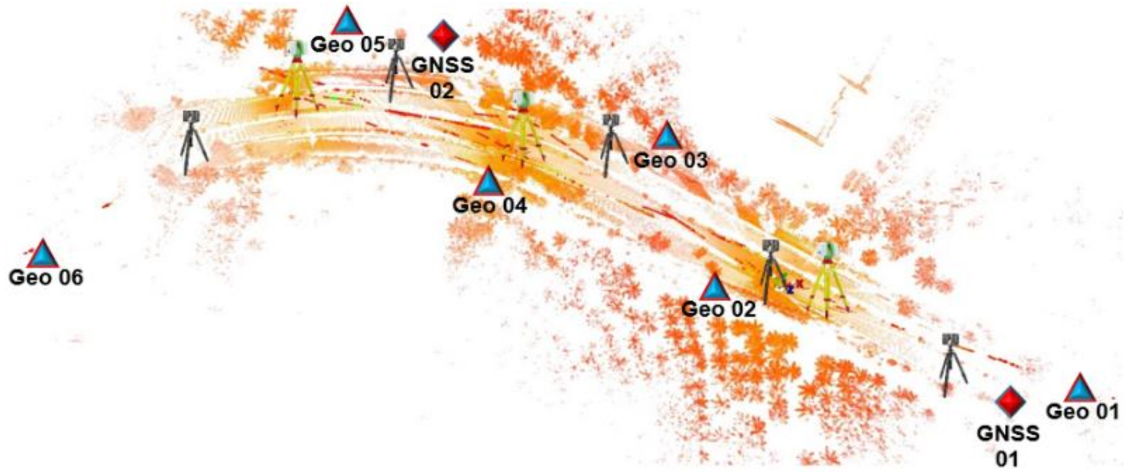

Fig. 5. Multi sensors experiment held at Universiti Teknologi Malaysia, Malaysia.

(a)

(b)

Fig. 6. Multi sensors experiment using phase based (a) and pulse based (b) scanners.

Acquired data from both scanners were pre-processed using Leica Cyclone 7.3. To thoroughly examine the findings of multi sensors experiment, all six (6) georeference points have been group as follows: i) 1, 2, 3 and 4; ii) 1, 2, 5 and 6; iii) 1, 3, 4 and 6; iv) 3, 4, 5 and 6; and v) 1, 2, 3, 4, 5 and 6. With various network configuration, datum transformation of both scanners were computed using resection method. Scale factor produced from each georeferencing network procedure was extracted and investigate using statistical analysis. The statistical test was conducted to thoroughly examine the similarity of yielded scale factors with the ideal value (i.e. one).

3.3. Statistical Analysis

The crucial element of this research is to robustly validate the insignificant of scale factor in TLSs datum transformation. Hence, the selection of analysis was made by considering the capability to evaluate the similarity of the calculated scale factor (yielded from least square adjustment) and ideal value (i.e. one or no scale error). Ghilani [20] did mention that t distribution was utilised to equate the mean values obtained from population and sample set with respect to the number of redundancies. In this case, this test was therefore appropriate to evaluate the computed scales (sample mean) against an ideal value (population mean). The analysis of t-test can be performed using formula [20]:

$$t = \frac{\bar{y} - \mu}{S/\sqrt{n}} \quad (3)$$

where:

$\bar{y}$ = Computed scale factor.
μ = Ideal value of scale factor (i.e. one).
S = Precision of sample.
n = Number of sample.

The hypothesis employed for this the test is:
H_0 : The computed scale factor is equal to ideal value.
H_A : The computed scale factor is not equal to ideal value.

The alternative hypothesis (H_A) will be accepted if the calculated t value (Eq. (3)) is larger than the tabulated t value (obtained from the t-distribution table) with selected confidence level. Rejection of H_0 indicate that the computed scale factor is statistically different with ideal value (acceptance of alternative hypothesis, H_A).

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4. Results and Analyses

Investigation of scale factor affect in TLSs datum transformation procedure was made by taking into account two (2) crucial elements, multi distances and sensors. Therefore, research findings have been organised based on these elements as discussed in the previous section.

4.1. Multi Distances

The first experiment was carried out by employing various ranges of scanning stations from the distributed targets. Both phase-based and time-of-flight scanners were gradually shifted for every 10m until 60m. With relatively less error in range measurement and best resolution of point clouds acquired compare to the others (i.e. 20m until 60m scanner positions), 10m scanner position has been assigned as reference for all registration procedure. Figure 7 depicted the errors of computed scale for 20m until 60m ranges. Maximum scale errors for phase-based and time-of-flight scanners are 0.001 and 0.0004, relatively. It is unexpected when the largest errors for both scanners were contributed by 40m scanner position (should be from farthest scanner position, 60m). However, based on the condition of that largest uncertainty scanner position, this error occurred due to the high exposure of light as found by Lemeš and Zaimović-Uzunović [21]. Disregard ambiguity occurrence, at 95% confidence level, the statistical test has mathematically verify that the computed scale factors (obtained from 20m until 60m scanner positions) have shown significant similarity to the ideal value (i.e. one). Table 1 and Table 2 have tabulated the values of calculated t against critical t, in all circumstances the alternative hypotheses have been rejected. With acceptance of null hypothesis, it can be concluded that through multi distances experiment, the scale factor has arithmetically proved that it is negligible in TLSs datum transformation.

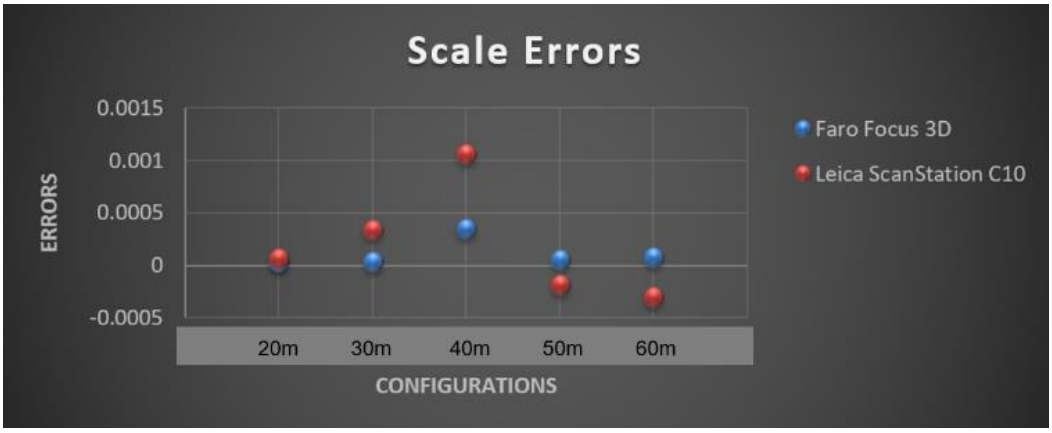

Fig. 7. Scale errors in multi distances experiment for both phase and pulse-based scanners.

Table 1. Multi distances statistical test for pulse-based scanner (i.e. Leica ScanStation C10).

Configuration	Scale	DoF	Calculated T	< / >	Critical T
20m	1.000065	11	0.228666	<	2.201
30m	1.000338	11	0.513983	<	2.201
40m	1.001061	11	0.385331	<	2.201
50m	0.999815	11	0.181687	<	2.201
60m	0.999697	11	0.272587	<	2.201

Table 2. Multi distances statistical test for phase-based scanner (i.e. Faro Focus 3D).

Configuration	Scale	DoF	Calculated T	< / >	Critical T
20m	1.000042	11	0.079196	<	2.201
30m	1.00004	11	0.042278	<	2.201
40m	1.000351	11	0.612826	<	2.201
50m	1.000062	11	0.069258	<	2.201
60m	1.000077	11	0.070345	<	2.201

4.2. Multi Sensors

As mentioned earlier, different kinds of sensors have been equipped with their own mechanism in measuring range. The contrast in range measurement approaches will result error of scale factor in datum transformation. In order to robustly examine this multi sensors effect in TLSs georeferencing procedure, this study has employed GNSS, total station and TLSs measurements.

In order to achieve quality results in GNSS observation, there are certain criteria that needs to be emphasized. Those criteria that have been adopted are good clearance of sky view to avoid multipath error, the duration of the observation to increase redundancy in measurement, and the geometry of satellites tracked by the receiver. All these criteria are crucial to ensure the quality of data collected. As shown in Table 3, results of GNSS observation have indicated that root mean squares (RMSs) for both horizontal and vertical are in good condition as the values of both horizontal and vertical RMSs are consider small for both points (i.e. GNSS01 and GNSS02). Thus, it can be conclude that both GNSS points that have established using Rectified Skew Orthomorphic (RSO) geocentric coordinate system (for horizontal) and orthometric height (for vertical) have obtained the required quality (i.e. sub-centimetre).

Table 3. Quality of established georeference points using GNSS observation.

Name	RSO Geocentric			Orthometric Height	
	North (m)	Easting (m)	Horizontal RMS (m)	Height (m)	Vertical RMS (m)
GNSS01	172129.333	628106.384	0.002	17.645	0.004
GNSS02	172148.751	628444.568	0.001	24.488	0.002

Those GNSS coordinates were transferred to all six (6) georeference points using total station measurement (i.e. traversing method). From twelve (12) traverse points, least square adjustment was employed to derive thirty (30) unknown parameters from hundred and twelve (112) observations. After two iterations, the adjustment was converge and has passed global test at 95% confidence level (Fig. 8). Table 4 has presented the results of adjusted coordinates obtained from STAR*NET software. Similar to GNSS results, largest standard deviation (0.004m) of adjusted data is lie within expected threshold (i.e. sub-centimetre).

Employing two types of scanners (phase and pulse based), the final experiment was performed to analyse the effect of scale factor in georeferencing procedure via multi sensors experiment. There are six (6) georeferenced points were well distributed for this evaluation. Based on the established georeference points, datum transformation computations were performed using five (5) configurations. Scale errors obtained from each configuration were plotted in Fig. 9 and as expected, due to the network configuration (distribution of targets) exploited [16], the trend has shown excellence results where the largest scale errors obtained are 0.00013 and 0.0002 for Leica ScanStation C10 (pulse-based) and Faro Focus 3D (phase-based), respectively. Based on Table 5 and Table 6, statistical analyses for both TLSs have verified that at 95% confidence level shows that computed scale factors for all georeference configurations were significantly similar to ideal value (i.e. one or no scale effect). With these findings, final conclusion can be made that scale factor is insignificant in TLSs datum transformation.

Table 4. Adjusted coordinates obtained from STAR*NET software.

Station	N (m)	σ_N (m)	E (m)	σ_E (m)	Elevation (m)	σ_{Elev} (m)
1 (GNSS 01)	172129.333	0.000	628106.384	0.000	17.640	0.000
2	172139.701	0.001	628205.980	0.003	18.843	0.002
3	172143.003	0.001	628356.698	0.004	20.646	0.002
4	172166.691	0.002	628456.271	0.001	20.323	0.001
5 (GNSS 02)	172148.751	0.000	628444.568	0.000	24.488	0.000
6	172120.877	0.001	628248.637	0.003	19.423	0.002
Geo 01	172120.107	0.002	628099.050	0.002	17.411	0.001
Geo 02	172144.642	0.001	628196.679	0.003	20.525	0.002
Geo 03	172113.451	0.001	628270.693	0.003	22.775	0.002
Geo 04	172153.659	0.001	628354.695	0.004	25.781	0.002
Geo 05	172159.694	0.001	628461.811	0.002	24.012	0.001
Geo 06	172255.281	0.003	628506.798	0.002	20.487	0.003

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              Adjustment Statistical Summary
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             Iterations                 =      2

             Number of Stations         =     12

             Number of Observations     =    112
             Number of Unknowns         =     30
             Number of Redundant Obs    =     82

Observation    Count    Sum Squares         Error
                          of StdRes         Factor
     Angles       48        11.907          0.582
  Distances       16        55.531          2.177
    Zeniths       48        39.794          1.064

      Total      112       107.231          1.144

      The Chi-Square Test at 5.00% Level Passed
           Lower/Upper Bounds (0.847/1.153)
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Fig. 8. Least square adjustment summary for traversing measurement.

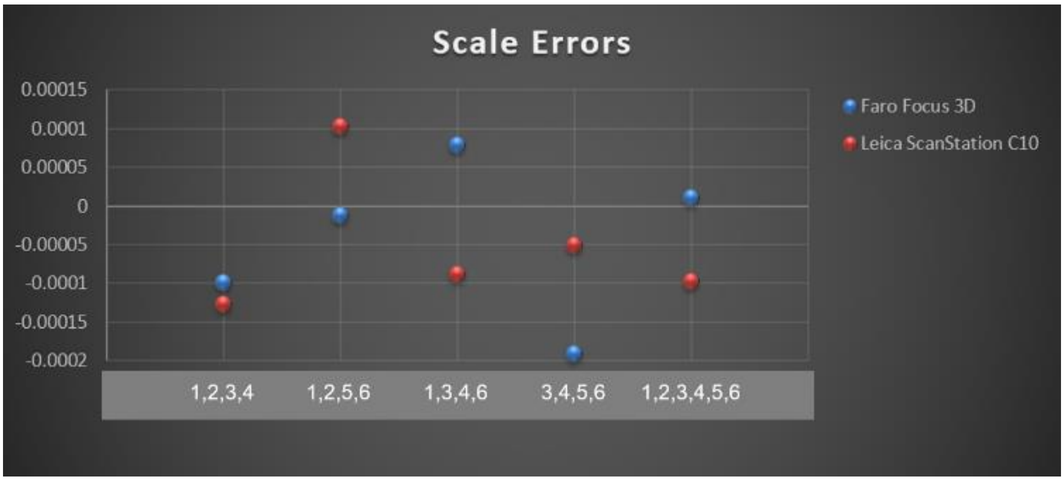

Fig. 9. Scale errors in multi sensors experiment for both phase and pulse-based scanners.

Table 5. Multi sensors statistical test for Leica ScanStation C10 (pulse-based scanner).

Configuration	Scale	DoF	Calculated T	< / >	Critical T
1,2,3,4	0.9999	5	0.24464	<	2.571
1,2,5,6	0.999987	5	0.00197	<	2.571
1,3,4,6	1.000079	5	0.006075	<	2.571
3,4,5,6	0.999808	5	0.010926	<	2.571
1,2,3,4,5,6	1.00001	11	0.000834	<	2.201

Table 6. Multi sensors statistical test for Faro Focus 3D (phase-based scanner).

Configuration	Scale	DoF	Calculated T	< / >	Critical T
1,2,3,4	0.9999	5	0.24464	<	2.571
1,2,5,6	0.999987	5	0.00197	<	2.571
1,3,4,6	1.000079	5	0.006075	<	2.571
3,4,5,6	0.999808	5	0.010926	<	2.571
1,2,3,4,5,6	1.00001	11	0.000834	<	2.201

5. Conclusions

Taking into account the uncertainties that can affect the quality of range data in TLSs measurement, neglecting scale factor in datum transformation computation could jeopardise the data. This study has quantitatively scrutinised the significance of scale factor in TLSs pre-processing procedure using both phase-based and time-of-flight scanners. Both experiments (i.e. multi distances and multi sensors) have obtained similar outcomes, through statistical analyses, null hypotheses have proved that at 95% confidence level, the scale factor is not significant in TLSs datum transformation. This conclusion is limited to medium range scanners, further investigation for long range TLSs are crucial to scientifically prove the insignificant of the scale factor. Nevertheless, there are several findings from this study that need to be considered for TLSs data quality assurance, from the first experiment (i.e. multi distances) it has shown that the effect of light can affect the quality of data, while later experiment (i.e. multi sensors) has indicated the requirement of well distributed targets to derive the transformation parameters.

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