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Quantitative Evaluation of Scaling Factor on Coordinate Transformation for Time-of-Flight Terrestrial Laser Scanner

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Abstract Terrestrial laser scanning is a new approach in three-dimensional measurement. Since the acquisition of terrestrial laser scanner data requires multiple scanning stations to complete the data of a scanned object, the coordinate transformation process is the inevitable procedure in the measurement phase of the laser scanner. However, neglected scale factors in the process of terrestrial laser scanning datum transformation have led to a dispute over the quality of the laser scanning data. Emerging of errors not only occurs during data collection phase but it also occurs during data processing phase involving the use of algorithms. For a comprehensive assessment of these scale factors, two experiments have already been conducted involving multiple-networks experiment and multi-distance experiment. Multiple network experiment is performed with the establishment of multiple scanning stations (from 2 to 7 stations) and some real object surfaces equipped with artificial targets. The multi-distance experiment involves various scanning distances provided by the time-of-flight terrestrial laser scanning, involving testing from 60m to 140m. The registration process is then performed to produce all 7 parameters including the scale factor calculated between the scanner positions. The statistical method, with hypothesis testing, is used to evaluate the scale factor that is calculated with the ideal value. The results show that in all configurations, the null hypothesis is accepted with a 95% confidence level. This result also stipulates that scale factor can be ignored in datum transformation process for terrestrial laser scanning.

Keywords Datum Transformation, Scale Factor, Significant Test, Time-of-Flight Scanner

1. Introduction

Embraced as a non-contact sensor, terrestrial laser scanner (TLS) has become the user's primary tool when it is involves with three-dimensional (3D) data acquisition. The capability to provide dense and rapid (up to one million points per second) and direct 3D measurement without any extensive manual editing and extrapolation has made TLS applicable for various of applications. According to Genechten [1], applications of TLS can be categorised based on the range covered by the scanner as depicted in Figure 1. Currently, there are three different mechanisms employed in obtaining range from TLS measurement [2]:

a. Time of flight (for long range);
b. Phased (for medium range);
c. Triangulation (for close range).

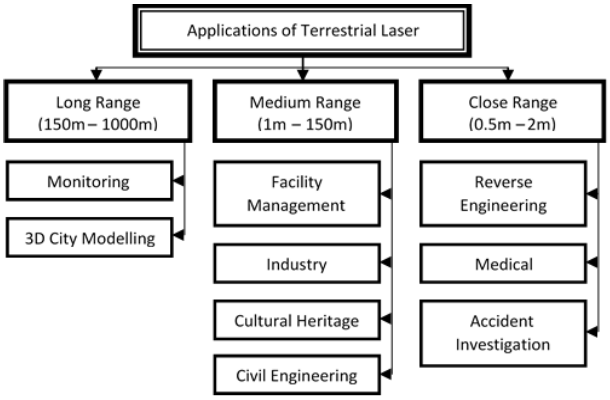

Figure 1. Classifications of TLs based on range mechanism [1]

Measurement techniques above have been exploited to classify applications of TLSs. Long range scanners that adapt time of flight or pulse based mechanism capable to measure range from 150m up to 1000m, while phase scanners which used for medium range able to acquire range from 1m until 150m and the most accurate of all, triangulation scanners have ranged from 0.5m until 2m.

For the long range applications, accuracy requirement for monitoring work and 3D city modelling are quite differ. Monitoring utilised to measure small movement of the object or structure while city modelling just focus on visual presentation. In order to evaluate the quality of perfectness of the measured object, monitoring application demand sub-centimetre geometric accuracy. For instance, Artur et al. [3] has performed reliability investigation of TLS in monitoring of surfaces deviation and displacements of marked point of construction of a concrete water dam.

Obtained data were then used to create and update geometric model of structure behaviour under variable loads, and identify relation of water level and structure geometry. From the findings, authors have conclude that the specific character of hydrotechnical facilities is a need for specific patterns and develop its own methods of measurement using laser technology. Riveiro et al. [4] exploited long-range scanner system in masonry arch bridges data acquisition, modelling and analysis. Significant of TLS (i.e. non-contact sensor) has been demonstrated when the study involved with situation to obtain data from collapsing load and its position as well as the reaction forces at the abutments. The acquired dense 3D data are essential in for further stages, in order to identify optimal location for the strengthening. Another example of structure health monitoring was conducted by Bonali et al. [5], TLS was employed to detect deformation patterns of ancient building. Taking into account the rapid data acquisition, simple in instrument handling, safe measurement approach and analysis capability has indicated the potential of TLS measurement. Authors suggested that this measurement approach could be adopted as a protocol for civil protection interventions. Not limited to geodetic applications, Nagalli et al. [6] have introduced TLS for geotechnical purposes. Scanning data was acquired to evaluate slope stability in terms of planar failure. The results show the advantages of using TLS due to the ability to work with large data amount simultaneously with the same precision. Yang et al. [7] have employed TLS measurement to improve reliability of composite structural deformation monitoring. Differ with traditional monitoring approaches, TLS has capability to provide better flexibility especially in actual data acquisition. Due to the limitation of some embedded sensors which failed after running several years, authors has proposed TLS measurement as supplement or even substitute of the traditional monitoring methodologies. A series of statically experiments under monotonic loads measurement based on TLS are performed to examine the deformation behaviour of arch structure. The results from thirteen epochs of data indicated that TLS was capable of acquiring data similar the actual situation.

Employing any kinds of sensors, it is often occurred where complete data that cover the whole surface of the object cannot be obtained from a single station. Minimum two stations are required and most of the time, number of occupied position was determine based on the complexity of the object. It is directly proportional, complex object will demand more station number. Thus, similar principle was applied in TLS measurement, and this will result multi local coordinate systems generated for each scanner position. For visualization and enhancement, all scanned data (which based on local coordinate system) are required to be projected into one common global coordinate system. This procedure is known as registration and according Elkhrachy [8], mathematics involve can be designated by a rigid body transformation algorithm. Relation between adjacent scan stations can be derived based on six (6) parameters (by neglecting scale factor) as follows [2]:

a. Translation for the 3 dimensional axes (Δ_X, Δ_Y, Δ_Z); and
b. Rotation around the 3 dimensional axes (ω, φ, κ).

Data quality assurance is mandatory for any kind of data acquisition to guarantee the accuracy obtained was sufficient according to the job requirements. This principle was applied in geomatics jargon where consideration was made that the results yielded can be augmented by various systematic error sources, even in newer instruments [9]. Furthermore, errors are not only be yielded from the instrument itself, the processing procedure involving with algorithm can also contribute for the uncertainty. For instance, derivation of transformation parameters using poor network can cause a weak solution [10], false determination of target centroid due to the less resolution [11], algorithm for form fitting has wrongly identify the object [12] and vegetation filtering procedure that wrongly remove the ground data. Thus, investigation of errors should not only limited to the sensor but including the algorithm involves in the processing phase. Similar consideration should be applied to TLS registration procedure, neglecting scale factor especially in long range application that demand high accuracy data is irrelevant. According to Rueger [20], scale errors in range measurement are primarily caused by the oscillator and transmitter diodes. However, it should be noted that there are external effects that contribute to a large number of scale errors. With complex mechanism employed by TLS in providing non-contact (reflectorless) dense 3D data, it is expected that many effects can cause scale errors in range measurement, such as high incidence angle, environmental factors, erroneous geometrical reduction (e.g. dependency on point cloud resolution to determine target centroid), among others. Based on that argument, further investigation is necessary to robustly prove that contribution of scale factor in TLS rigid body transformation is insignificant. Taking into account the range that can be covered by the time of flight (TOF) scanner and the mechanism utilised in deriving range measurement, it can be assumed that TOF scanner is more susceptible to scale errors than others. For such purpose, this study focused on quantitative investigation of scale factor for time of flight scanner (Leica ScanStation C10). To ensure the evaluation was performed rigorously, two types of experiments were utilised using multi networks and multi distances. Statistical analysis was employed to concretely verify the results obtained from the experiments.

2. Time-of-Flight Scanner

Differ from photogrammetry approach, scanner is an active sensor the uses laser light to probe the subject. As mentioned in previous section, TLS can be classified based on distance measurement system: i. Time of flight; ii. Phase; and iii. Triangulation. Among all kinds of TLS, triangulation scanner was equipped with mechanism to provide the best accuracy, follow with phase based scanner and time of flight is the worst [8]. When it goes to the range covered by the scanners, the accuracy rank is inversely proportionate. Time of flight technique can measure a kilometre in distance, in addition, in line with technology progress, the accuracy also improved until sub-centimetre level [11].

Mechanism of time of flight scanner is quite simple. As illustrated in Figure 2, range is determine from travel time Δt of a pulse of light transmitted to the object and return back to the scanner [13]:

$$\text{Range} = \frac{c}{2} \times \Delta t \qquad (1)$$

where c is the speed of light. The temporal accuracy has to be high due to fast speed of flight (c ≈ 3 x 108 m/s).

The advantage of time of flight scanner from utilising time of flight is the possibility of transmitting a high amount of energy in a very short time [8]. Thus, a high short-term optical signal-to-noise ratio (SNR) is attained while maintaining a low mean value of optical power. This is very crucial to reduce the demand on a very high sensitivity and SNR of the detector, thus enabling long range measurement. The range accuracy of time of flight (or pulse based) system is relatively constant for the whole volume and basically limited by how well electronics can solve time. Standard deviation for the range measured using pulse based (σRP) TLS is given approximately by the following equation [14]:

$$\sigma_{RP} = \frac{c}{2} \times \frac{T_r}{\sqrt{SNR}} \qquad (2)$$

where T_r is a pulse rise time. According to Al-Manasir [15], the accuracy of pulse based measurement technique is directly related to the amplitude of the returned signal (SNR). The uncertainty associated with each single measurement can be reduced by increasing the number of samples for each measurement. Final measurement is represented by an average of sample measures. Value of σ_{RP} can be reduced by a factor proportional to the square root of the number of samples. There are three major factors which govern the accuracy of a pulsed based measurement technique namely:

a. Ability to select the same relative position on the transmitted and received pulse to measure the time interval. This is limited by noise, time jitter, signal strength and sensitivity of the threshold detector, and shortness and reproducibility of the transmitter pulse;
b. The accuracy with which fixed time delays in the system are known; and
c. The accuracy of the time interval measurement instrument.

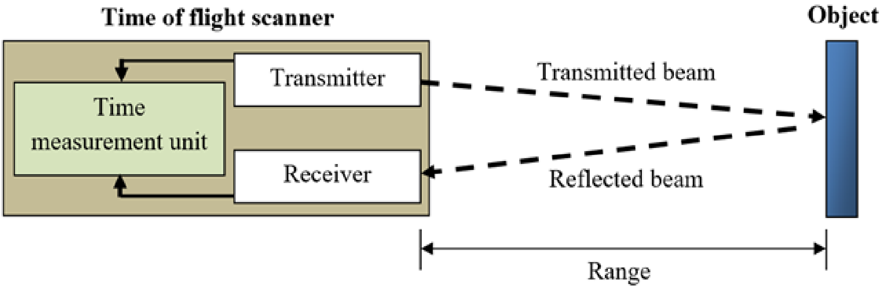

Figure 2. Mechanism of time of flight scanner

3. Datum Transformations

A rigid body transformation or 3D conformal coordinate transformation employ for converting 3D coordinates from one system into another one. Figure 3 depicted transformation of local coordinate system TLS1 into TLS2, transformation parameters are derive from three (3) well-distributed common targets using resection method.

Raw data provided by the TLS are range (r), horizontal direction (ϕ) and vertical angle (θ), which are in spherical coordinate system. Therefore, the functional models involved in order to convert between Cartesian and spherical coordinates system can be expressed as follows [16]:

$$r = \sqrt{x_{ij}^{2} + y_{ij}^{2} + z_{ij}^{2}} \quad \textbf{(3)}$$

$$\phi = \tan^{-1}\left(\frac{x_{ij}}{y_{ij}}\right) \quad \textbf{(4)}$$

$$\theta = \tan^{-1}\left(\frac{z_{ij}}{\sqrt{x_{ij}^{2} + y_{ij}^{2}}}\right) \quad \textbf{(5)}$$

where x_{ij}, y_{ij} and z_{ij} are coordinates of targets in scanner coordinates system. Values of x_{ij}, y_{ij} and z_{ij} have to be substituted by the following equation in order to express the original laser scanner observations as function of the position and orientation of the laser scanner in a global coordinate system.

Based on rigid-body transformation, for the jth target scanned from the ith scanner station, the equation will look as follows [8]:

$$\begin{aligned} x_{ij} &= S[R_{11}(X_j - X_{Si}) + R_{21}(Y_j - Y_{Si}) + R_{31}(Z_j - Z_{Si})] \\ y_{ij} &= S[R_{12}(X_j - X_{Si}) + R_{22}(Y_j - Y_{Si}) + R_{32}(Z_j - Z_{Si})] \\ z_{ij} &= S[R_{13}(X_j - X_{Si}) + R_{23}(Y_j - Y_{Si}) + R_{33}(Z_j - Z_{Si})] \end{aligned} \quad \textbf{(6)}$$

where:

$\lfloor x_{ij} \quad y_{ij} \quad z_{ij} \rfloor$ = Coordinates of the jth target in the ith scanner coordinate system.

S = Scale factor.

$_3R_3$ = Components of rotation matrix between the two coordinate systems for the ith scanner station.

$\lfloor X_j \quad Y_j \quad Z_j \rfloor$= Coordinates of the jth target in the global coordinate system.

$\lfloor X_{Si} \quad Y_{Si} \quad Z_{Si} \rfloor$ = Coordinates of the ith scanner station in the global coordinate system.

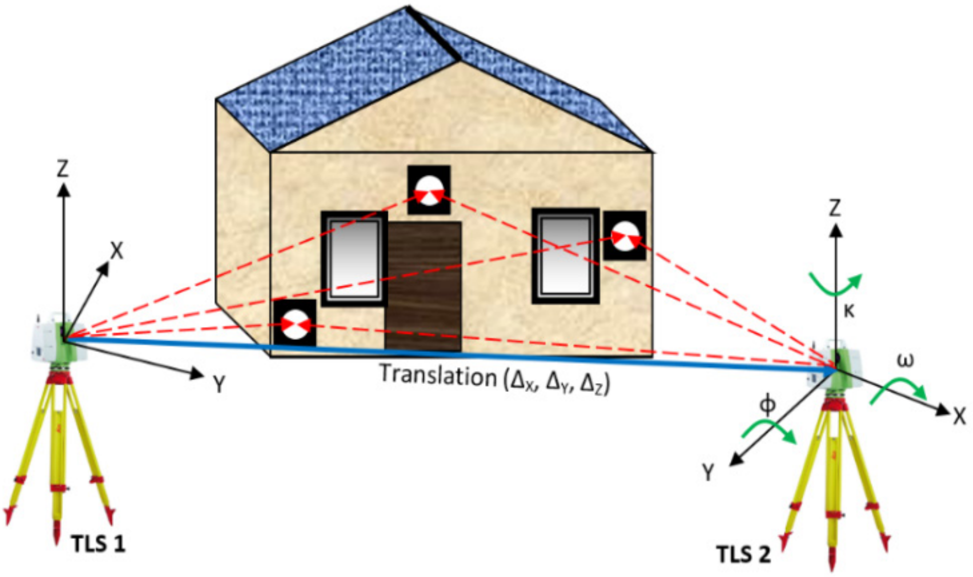

Figure 3. Determination of transformation parameters

4. Experiments

As mentioned earlier in Section 1, the aim of this study is to verify the significant of scale factor in TLS datum transformation which focused on TOF scanner. For that purpose, Leica ScanStation C10 was utilised for two kinds of experiments as follow:

a. Multi network configurations; and
b. Multi distances assessment.

Considering the primary caused and external effects that can contribute to the scale errors in TLS range measurement, each experiment was designed for a specific reason. Taking into account the effects of high incidence angle and erroneous in the geometrical condition in TLS scanning procedure, multi network configurations have been designed by considering two elements: i. Occupied stations; and ii. Surfaces for target distribution. As for measuring primary scale errors caused, later experiment was utilised to assess any uncertainties with regard to various distances. To evaluate the significant of the calculate scale factor with ideal scale value (i.e. one), this study has utilised t-test.

4.1. Multi Network Configurations

The idea of multi network configurations experiment is to robustly evaluate the significant of scale factor in various conditions. As depicted in Figure 4, the experiment was carried out at laboratory with dimension, 15 m (length) × 9 m (width) × 3 m (height) which located at Faculty of Geoinformation and Real Estate, Universiti Teknologi Malaysia. Criteria of network configurations were designed as follow:

a. Number of scan stations; and
b. Number of surfaces.

To avoid any redundancy, final configuration of previous criteria was employ for the next configuration. For example, if final setup for the first configurations (scan stations) is using two (2) stations, thus, second configurations (surfaces) will continue with similar number of station.

Figure 4. Multi network configurations experiment

4.1.1. Number of Scan Stations

For the first configuration, all 134 artificial targets distributed at all four (4) wall and a ceiling were measured from seven (7) scan stations (Figure 5a). To variate the number of scan stations, following setup was implemented by reducing number of scan stations one by one until two scan stations left (Figure 5b). To yield the value of transformation parameters for each sub-configuration, the self-calibration bundle adjustment is performed for every reduction of scan station. Statistical analysis was utilised to thoroughly examine the significant of scale factor for every bundle adjustment (configuration) results.

4.1.2. Number of Surfaces

Number of surfaces configuration was carried out by reducing the number of surfaces used to attach all 134 artificial targets. As mentioned earlier in previous section, four (4) wall and a ceiling were used to distribute all targets. Thus, this experiment was performed by manually removing those surfaces one by one until two surfaces were left as shown in Figure 6. To maintain the quality of the calculated transformation parameters, reduction criteria was made by taking into account guideline of network configuration as discussed in [17]. For each removing process, bundle adjustment was performed and followed with scale factor analyses.

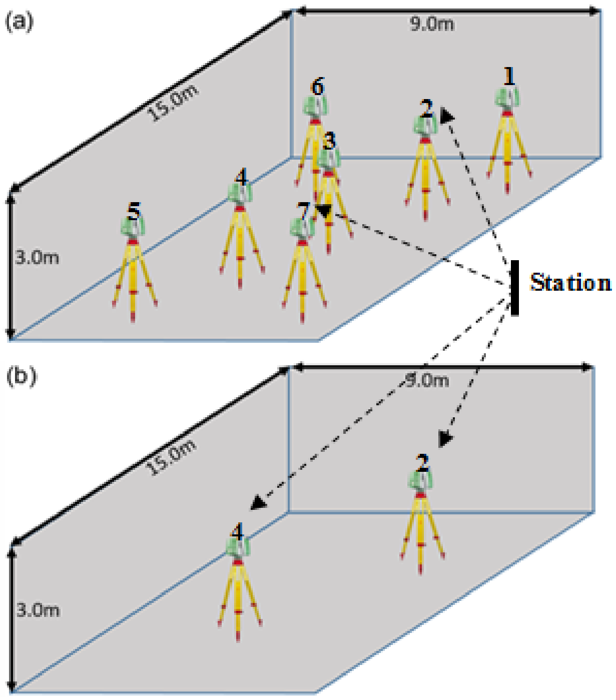

Figure 5. Reducing number of scan stations, (**a**) Seven, and (**b**) Two scan stations

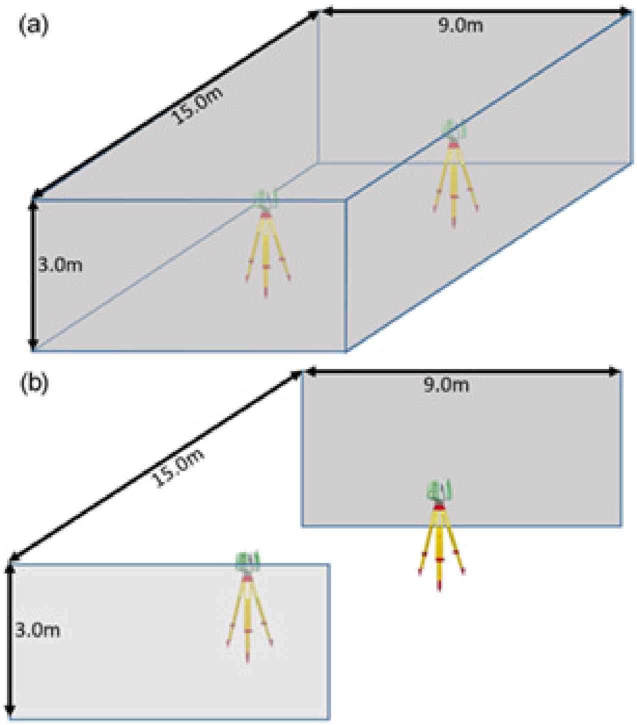

Figure 6. Reducing number of surfaces for targets distribution, (**a**) Four surfaces by removing a ceiling, and (**b**) Two surfaces

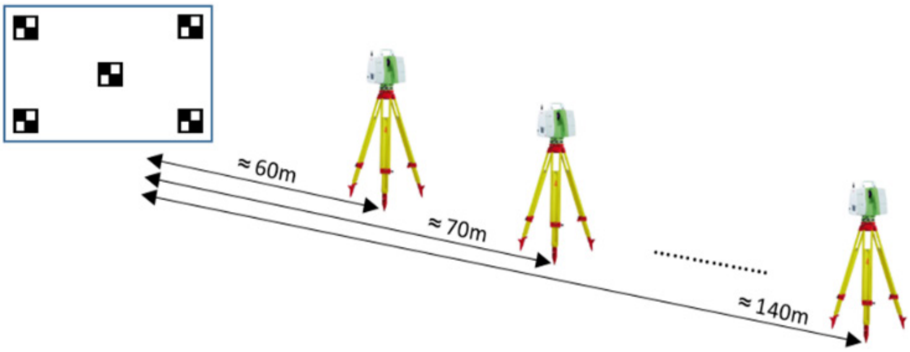

Figure 7. Network configurations for multi distances assessment

4.2. Multi Distances

For multi distances assessment, eight (8) targets were distributed at the slope located at Faculty of Electrical Engineering, Universiti Teknologi Malaysia. The aim of this experiment was to investigate the scale effect in TLS datum transformation with respect to various distance, especially when the scanner was far away from the targets. As illustrated in Figure 7, the measurement was started roughly 60m from targets, the procedure was continue by moving the scanner at 10m interval until maximum distance 140m. Registration process was made using pairwise approach and targets extracted from 60m distance were employed as reference for other configurations. All eight (8) scale factors obtained from the experiment then were analysed in term of significance in TLS datum transformation.

4.3. Statistical Analysis

Selection of statistical test was made by taking into account the aim of the study which was to evaluate the similarity of the calculated and ideal values of scale factor. According to Ghilani [18], t distribution was used to compare population mean with the mean of a sample set based on the number of redundancies in the sample set. Thus, this test was applicable to examine a sample mean (calculated scale) against a known value (ideal scale value). Known as t-test, the analysis was performed using formula [19]:

$$t = \frac{\bar{y} - \mu}{S/\sqrt{n}} \tag{7}$$

where,

$\bar{y}$ = Sample mean
μ = Population mean
S = Standard deviation of sample
n = Number of sample

The hypothesis of the test is:
H_0: The sample mean is equal to population mean
H_A: The sample mean is not equal to population mean

When the calculated t value (7) is larger than the value of critical t (predicted from the t-distribution table), the null hypothesis (H_0) will be rejected with selected level of significance (confidence level 95% equal to 0.05 of significance level). With the rejection of H_0, the sample mean is statistically different with population mean (accept H_A).

5. Results and Analyses

The first set of experiments were conducted by reducing the number of scan stations and real-world planes for targets distribution. The scan stations were reduced from full networks which were seven to a minimum of two stations, while surfaces was reduce from four (4) walls and a ceiling into two (2) walls left. For each reduction procedure, statistical test was performed. The scale errors obtained were depicted in Figure 8 and 9 for multi stations and multi surfaces experiments, respectively. As illustrated in Figure 8, the largest scale error in multi stations experiment (0.0016) was contributed by station one (1) under five (5) scanner positions configuration (refer Figure 5c), while the others lie within and below of 0.001. Based on plotted scale errors for multi stations, the trend has significantly shown that this uncertainty (scale errors) occurred due to the high incidence angles in measuring the targets when the occupied station very close to the wall (i.e. station 1 and 5). When a later configuration (multi surfaces) performed, the scale errors have consistently dropped below 0.001 (as depicted in Figure 9). The first experiment has numerically and graphically proved the significance of high incidence angles in causing scale errors in TLS measurement. Nevertheless, conducted statistical test to determine whether the calculated scale factors are similar to the ideal value (i.e. 1) at a 0.005 level of significance has yielded contra results. As presented in Table 1 and 2, in all conditions computed values of t are smaller than the tabulated or critical t, thus, the null hypothesis can be accepted at 95 percent level of confidence. This statistical finding may be due to the magnitude of the obtained scale errors are very small but it is advisable to avoid the existence of high incidence angle to ensure the quality of TLS measurement.

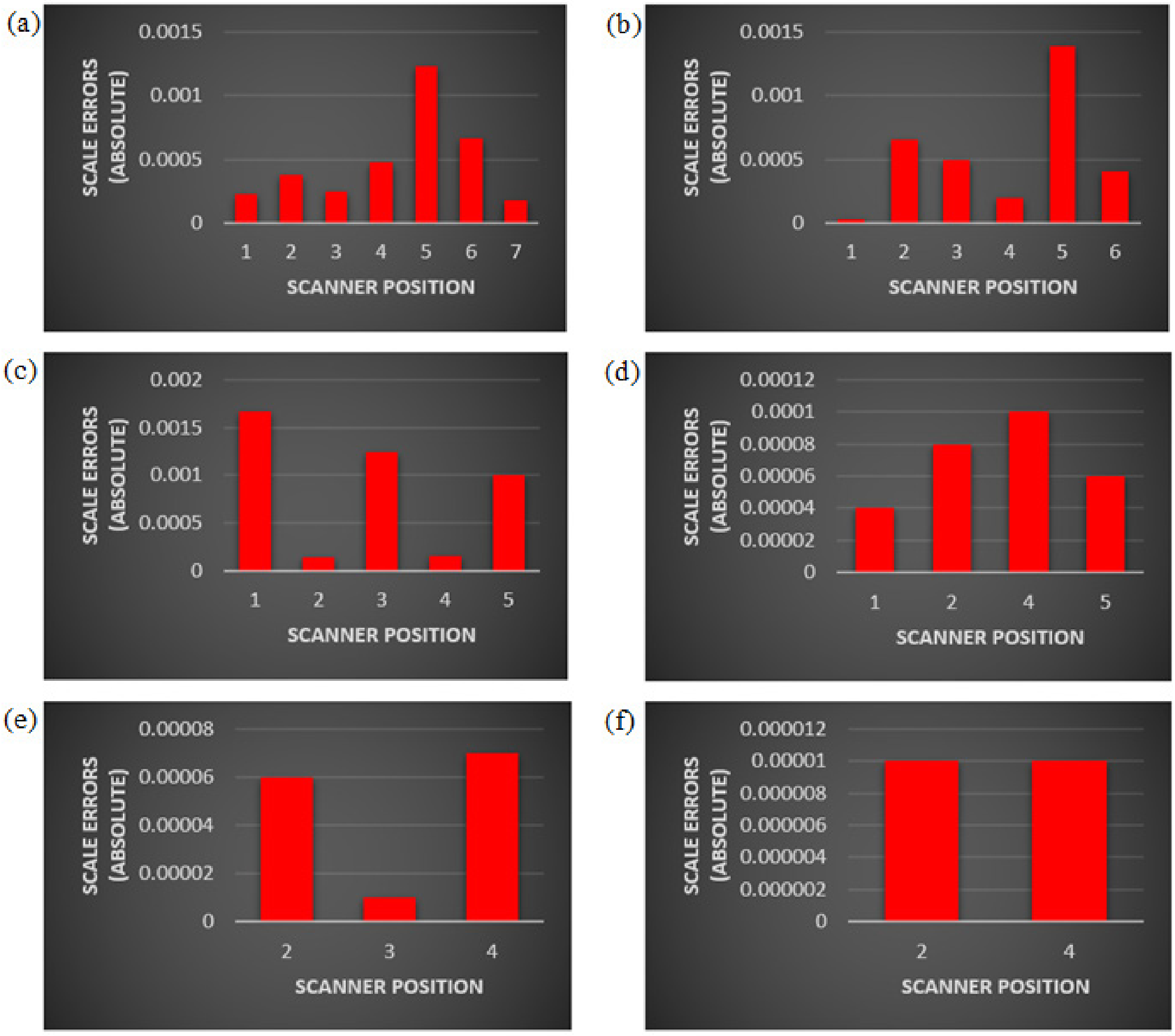

Figure 8. Scale errors for multi stations configuration, (**a**) Seven, (**b**) Six, (**c**) Five, (**d**) Four, (**e**) Three, and (**f**) Two scan stations

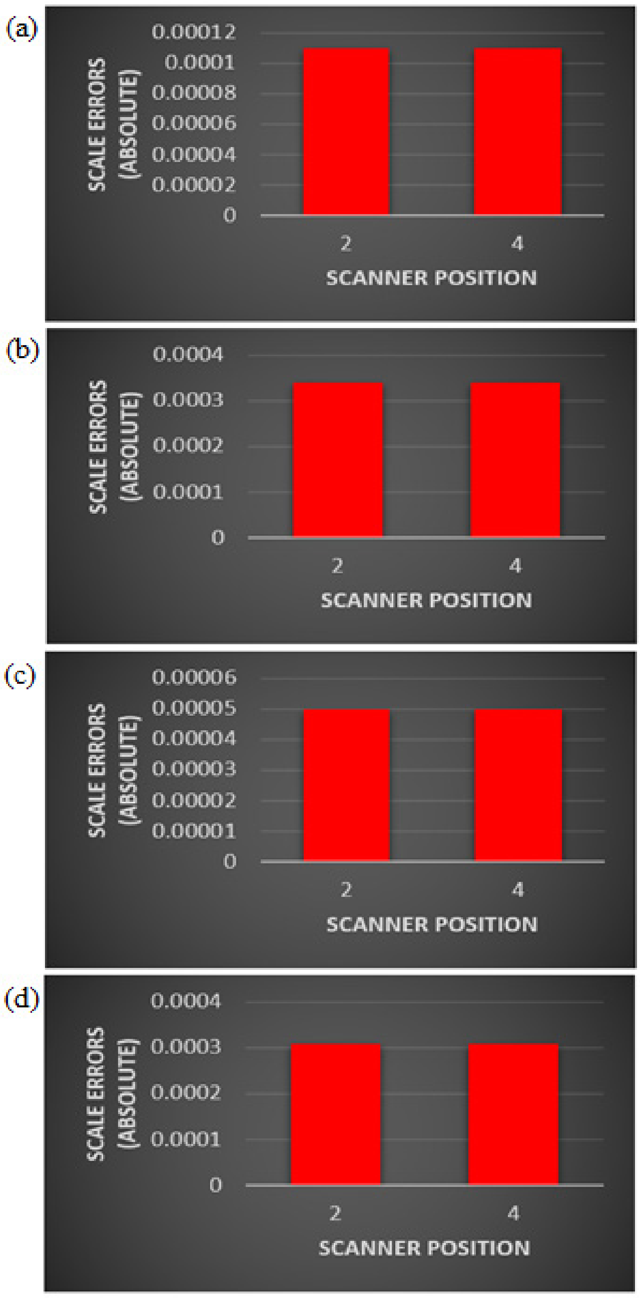

Figure 9. Scale errors for multi surfaces configuration **(a)** Four surfaces by removing a ceiling, (**b**) Three walls, (**c**) Two walls and a ceiling, and (**d**) Two surfaces

For the multi distances experiment, the scale factor was evaluated based on various distances from 60m until 140m. According to Rueger [20], the magnitude of scale error is directly proportional with distance, hence, the result obtained from this experiment is very crucial to understand the effect of scale factor in TLS datum transformation. Figure 10 presented the trend of scale errors obtained from the range of 70m until 140m. Parallel with Rueger [20] statement, plotted scale errors in Figure 10 is depicted linear increment when the ranges are gradually increasing from the surface where registration targets distributed. With relatively small magnitude of scale errors, as indicated in Table 3, similar to the results of previous experiments, at 95% confidence level the calculated t is smaller than critical t. With these findings, final conclusion can be made that scale factor is insignificant for pulse based scanner datum transformation. However, this study only focused on registration procedure which employing same sensor, the scale factor effect in georeferencing which involved with data captured from other sensors still unclear.

Table 1. Statistical analysis on scale errors for multi stations configuration

Scan stations	Calculated T	>or<	Critical T
Full networks	1.049	<	1.943
1, 2, 3, 4, 5, and 6	1.148	<	2.015
1, 2, 3, 4, and 5	1.789	<	2.132
1, 2, 4,and 5	0.816	<	2.353
2, 3, and 4	0.762	<	2.920
2 and 4	0.992	<	6.314

Table 2. Multi surfaces configuration statistical analysis

Surfaces	Calculated T	>or<	Critical T
4 walls	0.840	<	6.314
3 walls	0.282	<	6.314
2 walls and a ceiling	0.950	<	6.314
2 walls	0.883	<	6.314

Table 3. Statistical analysis on scale errors for multi distances

Configuration	Calculated T	>or<	Critical T
Multi Distances	1.741	<	1.895

Figure 10. Scale errors for multi distances configuration

6. Conclusions

Employing multi networks and multi distances experiments, the aim of this study is to robustly examine the significant of neglecting scale factor in TLS datum transformation. For data quality assurance, investigation of errors cannot be limited to the observation but including algorithms involves in processing. Existence of errors in any phase may propagate until the final product. Based on this argument, this study has performed significant analysis to the calculated scale factors which acquire in various configurations. The t- test, null hypothesis of all experiments showed that the scale factor yielded from time-of-flight scanner can be neglected. However, further study is necessary to evaluate this parameter when datum transformation involve with different scanners and sensors (e.g. total station, theodolite, camera and Global Navigation Satellite System).

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