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Spatial and Distance Discrepancies in Target-Based and Visual-Aligned LiDAR Models

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Today, static, terrestrial, Light Detection and Ranging (LiDAR) instruments are becoming more affordable and ubiquitous in numerous professional areas, including civil engineering, construction, architecture, surveying, archeological sites, and manufacturing, to name a few. Individual applications often require a greater or lesser level of accuracy, and many can present tolerance constraints that may rule out some available methodologies. Since most applications require to stitch (register) multiple scans into a common coordinate system, it is critical to examine various existing popular registration approaches to form expectations of the accuracies they will yield. This work studies the relative accuracy of two final point-cloud models of the same spatial conditions. Each model uses a different scan-stitching approach, the Target-Based (TB) registration and the Visual-Aligned (VA) registration. For comparison purposes, both models are georeference into the same State-Plane coordinate system. Point positions and distances, extracted from both final LiDAR models, are compared against the same positions and distances acquired in the field by an accurate Robotic Total-Station (RTS) instrument. This article presents those discrepancies and concludes that the TB registration is, approximately, 3 to 4 times more accurate than the VA one, when modeling a 3.5-acre site, via a closed scanning loop, under the conditions described in this project.

Key Words: Terrestrial, LiDAR, Target-Based, Visual-Aligned, Registration.

Introduction, Literature Review, and Objective

Land Surveying is among the oldest human professions. Their measurements require certain levels of accuracy and precision to qualify as acceptable deliverables. Spatial accuracy standards are established for both horizontal and vertical positions of points. These positions are to be compared against an independent source of higher accuracy and reported at a 95% confidence level (FGDC,1998). However, not every task requires the highest level of scrutiny. Some surveys can be completed with a lower accuracy tolerance. This depends on conditions, constraints, or the need for efficiency. Performance evaluation of tools and means is necessary to select the appropriate instruments and methods to be employed. Therefore, it is critical to evaluate the final accuracies attained via new instruments and surveying techniques.

This work studies relative accuracies of virtual, 3D point-cloud models generated by stitching several individual scans. Each of them was acquired by a popular, portable, terrestrial, LiDAR scanner, Leica Geosystems' ScanStation C10. This instrument uses numerous laser beams to digitally capture three dimensional (3D) shapes of objects located up to 300 m (984 ft) from itself. To fully cover the area of interest, most sites will require several scans, from different static stations. Each scan needs postprocessing to be cleaned, stitched (registered into a common system of reference) and, in some instances, the resulting models are to be georeferenced via appropriate software. This project used Leica's Cyclone Core software for postprocessing purposes, including the generation of georeferenced final models. The resulting models can be used as a virtual environment to measure and evaluate the existing conditions of a given site.

Though instrument manufacturers publish the accuracy of their products, it should be noticed that, in each project, the attained final accuracies differ from the manufacturer-indicated ones, as they focus on two distinctly different concepts (Walsh, 2015). It is known that final accuracies, after completing field operations/procedures, also depend on other factors, such as environmental conditions, collection strategy, and surface properties (Cosarea et al. 2009). More importantly, the magnitude of final errors also depends on the employed postprocessing procedures. This study investigates how two different data collection techniques, each associated with a different postprocessing registration approach, affect the accuracy of the resulting final LiDAR models. In this regard, two popular registration methods, employed by Leica Geosystems, are compared. They are the Target-Based (TB) and the Visual-Aligned (VA) approaches. They both can stitch all scans into georeferenced final models. The TB technique is based on the use of common target points in neighboring scans. These common points are matched to swiftly register all scans, at once, into the same coordinate system. On the other hand, the VA approach considers the full point clouds of two neighboring scans, per time, to register them via visual overlapping. This stitching is later enhanced by an error-minimizing algorithm. When compared against the VA technique, the TB approach requires considerably more time for data collection in the field, but minimum postprocessing time in the office. Therefore, depending on the availability of field or office time, users may prefer one or the other. However, they may result in different accuracies, as shown in this article. There are other registration procedures used by Leica's software, the automatic one and the Cloud-to-Cloud (CC) approaches. However, they are based on similar principles as those employed by the VA method.

Existing literature indicates that a 2014 article (Rajendra et al., 2014) evaluated partially overlapping 3D point cloud registrations using various cloud-based algorithms. It concluded that there was a high level of accuracy in the resulting models derived from cloud-based registration methods. However, their work did not consider Leica's VA registration approach, and did not use the same instruments employed in this project. Another study conducted in 2021, regarding the TB registration approach, comments on some problems with spherical targets such as those used in this study (Muralikrishnan, 2021). It explains that errors can be created by sphere targets due to inaccurately acquiring the center of the sphere at long distances. It also mentions that these targets tend to appear flared on the point clouds created by some scanners. However, in the present experiment, this was not observed while working with the C10 scanner. Additionally, in the current study, the maximum distance between the scanner and spherical targets was 112 m (367 ft). Furthermore, for the longest distances, the present work used 9-inch-diameter spheres. Conversely, for the short distances, typical 6-inch-diameter spheres were employed. Maldonado et al. (2022) presented discrepancies between georeferenced models via RTK and Static GNSS procedures. However, it did not study the accuracies of different registration methods. A newly developed registration approach, for pairs of scans, is based on shape matching. The investigators who studied its accuracy (Ogawa et al., 2019) concluded that the resulting errors ranged from millimeters to a few centimeters. Since this approach is not available in Leica's software yet, it was not part of the current study. Nevertheless, their reported errors are similar, in magnitude, to the ones presented in this article. Although the analyzed TB and VA registration approaches have been available for more than 15 years, users still have doubts about their relative accuracies. This is clearly observed in a relatively recent discussion at a well-known and popular online blog, Laser Scanning Forum (Kassler, 2021). Accordingly, the lack of information on the referred accuracies motivated this study.

The objective of this work is to consider a single case study (for a 3.5-acre site) to analyze the relative accuracies of two different registration (stitching) procedures, the TB and VA approaches, while working under similar weather conditions, and employing the same software from Leica Geosystems. The obtained results contribute to the existing knowledge by presenting sound statistical estimates of the final errors resulting from the use of the TB and VA registration approaches. The comparison presented in this article should assist surveying professionals in estimating the accuracies to be attained when using the TB or VA registrations for the generation of models similar in size and conditions.

The field and laboratory work for this study was performed as part of a service-learning project. The selected site is a 3.5-acre commercial area located in Statesboro, GA, known as the Herald Plaza. The project team consisted of both undergraduate and graduate students participating in a 5000-level Terrestrial-LiDAR introductory course. It involved students majoring in Civil Engineering, Construction Engineering, and Construction Management. The result of these efforts is being donated to the referred city and to a design firm to assist in potential rehabilitation tasks to benefit the community. Figure 1(a) and (b) show the site of the project and one of its final LiDAR models.

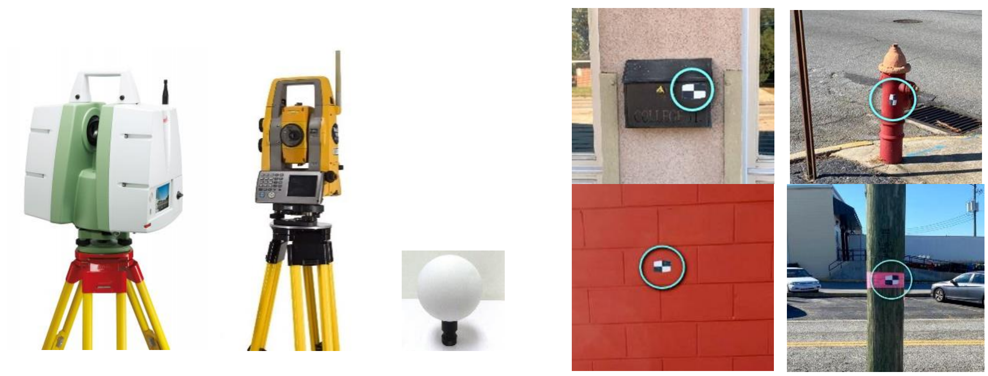
(a) Aerial View, Google Maps (b) Full Point-Cloud Model – Without Noise

Figure 1. Herald Plaza Project Site. North is Approximately Upward in Both Pictures.

Instruments and Methodology

Various instruments were employed in this project. They are shown in Figure 2(a). Point-cloud scans were completed using Leica Geosystem's ScanStation C10. This static scanner can capture up to 50,000 points per second (Leica, 2010), reflected from objects in a maximum range of 300 m (984 ft). Each full scan covered 360° horizontally and 270° vertically. Leica indicates that the C10 scanner has position accuracy of 6 mm (0.020 ft) and measurement accuracy of 4 mm (0.013 ft), both numbers are given in a one-sigma sense, for a distance range from 1 m to 50 m (3.3 ft-164.0 ft). Fifteen spherical targets (6-

inch and 9-inch-diameter ones) were used to capture the location of fixed Ground Control Points (GCPs). Leica's Cyclone Core software package was used for the processing of the acquired point clouds. A robotic total station (RTS) instrument, Topcon PS-103A, was supplied by an outside source and skillfully operated by a land surveyor, Mr. Zenan Merritt. His generous time and work are sincerely appreciated. The RTS device has an angular accuracy of 3 seconds, a reflectorless range of 1,000 m (3,281 ft) at an accuracy of 2mm+2ppm (0.78in+0.78in), with a 6-min dual-axis compensator. Its magnification is 30x. Since this is the most accurate measuring device in this study, it was employed as the benchmarking instrument to obtain field coordinates of multiple black-&-white sticker points. These fixed stickers served to determine and compare measured discrepancies between the LiDAR models and the RTS instrument. To acquire the coordinates of the 15 GCPs, a GNSS device was employed. This is the EGPS M7 base and rover. These GNSS instruments were also supplied by an outside source.



(a) Employed Main Instruments, from L to R: C10, PS-103A, and 6-inch Spherical Target

(b) Examples of black-&-white stickers

Figure 2: Main Instruments and Sample Black-&-White Sticker Points.

The following paragraphs describe the 5 main consecutive tasks involved in this work.

1 – GCPs and Fixed Stickers: First, the site was examined to plan the locations of scanning stations (34) and GCPs (15). The ground control points were distributed along the parking area, around the structure. The scanning locations were selected to capture as many GCPs as possible from each scan. Second, 45 adhesive stickers were placed on the structure and on some surrounding objects (i.e., posts, hydrants, etc.). Four of them can be observed in Figure 2(b). The purpose of those stickers was to serve as fixed points to compare their positions and distances when captured from each of the final LiDAR models (the TB and VA ones) versus their more accurate positions, as acquired by the RTS instrument. Third, the GNSS device was employed to determine the spatial coordinates of all 15 GCPs. Fourth, the RTS device was used to obtain the x-y-z coordinates of all 45 sticker points, via a resection procedure based on the coordinates of the GCPs. All mentioned coordinates were expressed in the Georgia East State Plane Coordinate System (GESPCS).

2 – Scanning: This project employed 34 scans to cover the 3.5-acre site. They were completed along a closed loop around the main existing buildings. Before each scan, spherical targets were positioned at several nearby GCPs, on verticalized poles. This was done to capture accurate positions of the GPCs points needed in the TB registration approach. Each 360° scan took approximately twelve minutes to complete. Additionally, each target associated with a particular GCP took about 5-6 min to acquire. All scans were medium resolution, with their point spacing set to 10 cm (0.33 ft), at 100 m (328.1 ft) from the scanner. Targets do not need to be captured when using the alternative VA registration approach. Thus, the VA scheme saves time in the field, but it requires more office time for postprocessing tasks.

The 34 scans were completed over a period of several days in similar moderately warm, partly cloudy, and dry conditions, during the months of September and October 2022. Therefore, it is estimated that weather conditions did not affect the relative comparisons presented in this study. The spherical targets were taken down and set back up during each visit to the site. Each scan was saved into the internal memory of the C10 instrument and later uploaded into Leica's Cyclone Core software for postprocessing tasks.

3 – Target-Based (TB) Registration Procedure: This registration scheme uses the spatial position of at least three common targets to stitch neighboring scans. The software translates and rotates all scans to make their common targets coincide as close as possible. This is a relatively fast approach. Since, in this project, a redundant number of common targets (≥3) were utilized in each pair of overlapping scans, this allowed operators to disable (disregard) a certain number of target connections (registration links) to improve the overall accuracy of the stitching procedure. The disabled links were those showing an error larger than 10 mm (~0.39 inches). The sources of these errors include small displacements of the targets, perhaps due to wind during scans, or due to small human errors while verticalizing the target poles. This situation shows the need to employ redundant target/control points to minimize errors that may affect the overall accuracy of the final models. The completion of the TB registration process yielded a full point-cloud model with arbitrary spatial coordinates for North (y), East (x), and Elevation (z). Later, the full model was georeferenced into the GESPCS. The final model resulting from this process is displayed in Figure 1(b).

4 – Visual-Aligned (VA) Registration Procedure: This process used the same scans as those in the TB registration approach. However, their stitching scheme did not require targets. This makes the VA technique faster than the TB one in the field. Nevertheless, the acquisition of some few targets was needed later to georeference the full VA model into the official GESPCS. Leica's VA stitching procedure consists in manually aligning two overlapping neighboring scans (point clouds), at a time, to form and grow a stitched group. For this, the software uses two alignment views, a horizontal plan view and an elevation side view. Each view shows a pair of selected overlapping neighboring scans, one in orange and another in blue. The user makes both point clouds coincide by manually translating and rotating them in each view. After this, the software refines this human alignment via an error-minimizing iterative algorithm. After this mathematical refinement, the software presents parameters estimating the accuracy of the completed merging process. Examples of those parameters are the total number of closely matched (or almost coincident) points and their root-mean-square error (RMSE). Various causes, such as the movement of vegetation in the wind, and the lack of overlapping between two neighboring scans, can make these parameters not attain desired small levels. This process was repeated until all scans were merged into a single model. This generated 69 connection links stitching the point clouds of all 34 scans. 65 of those links showed a maximum error of 10mm (0.39 in) with only 4 presenting larger errors, from 0.011 to 0.027 mm (i.e., from 0.43 in to 1.06 in). The clouds involving two of the latter links had a low number of overlapping points. Stitched scan pairs, within the 34 point clouds, showed a variable number of overlapping points, ranging from 343,733 to 1,573,166.

5 – Georeferencing and Data Postprocessing: The georeferencing of any fully stitched non-georeferenced point-cloud model (TB or VA) consists in reorienting it along a selected terrestrial system of reference. This procedure is similar to a TB registration because it requires stitching together two different point clouds using targets. One of the clouds is the non-georeferenced one of the full model and the other is a very small cloud containing only common targets (GCPs), at least 3 of them. The coordinates of those GCPs are to be in the selected terrestrial system of reference. In this work, to add redundancy, 6 common targets/GCPs were employed to georeference the full TB and VA models. However, when georeferencing the TB model, 2 targets/GCPs were disabled to attain errors ≤10 mm (≤0.39 in). Similarly, when georeferencing the VA model, 1 of the 6 targets/GCPs was disabled so all

errors were reduced to ≤13 mm (≤0.51 in). This process resulted in two different final georeferenced models, G-TB and G-VA, with coordinates in the same terrestrial system, GESPCS. The coordinates (positions) of the 45 stickers were extracted from each of the two final georeferenced models. They were in the GESPCS. Additionally, the field coordinates of those 45 stickers were also obtained in the GESPCS, via the RTS instrument. Therefore, for comparison purposes, each of the 45 stickers resulted with 3 sets of slightly different, x-y-z, spatial coordinates, all expressed in the same common terrestrial system of reference, GESPCS. These sets were postprocessed to determine position discrepancies between the G-TB model and the RTS coordinates. Also, position discrepancies were computed between the G-VA model and the RTS coordinates. Furthermore, all possible 995 non-repeated distances, among all 45 stickers, were calculated within each of the mentioned three sets. Then, distance discrepancies were determined between the G-TB model and the RTS instrument, and between the G-VA model and the RTS instrument. Finally, the main statistics of all discrepancies were calculated.

Results

Position Discrepancies

As indicated, the above methodology resulted in the acquisition of 3 sets of spatial coordinates (GESPCS) for each of the 45 common sticker points. Sets 1 and 2 were extracted from within the final G-TB and G-VA LiDAR models, respectively. Set 3 was acquired in the field, via a resection approach, with an accurate RTS instrument. Set 3 served as benchmark to compare the positions of the 45 sticker points twice: (i) the coordinates in set 3 were subtracted from the corresponding coordinates in set 1, and (ii) the coordinates in set 3 were subtracted from those in set 2. This generated two position-discrepancy vectors for each sticker, one comparing G-TB LiDAR vs RTS coordinates, and the other comparing G-VA LiDAR vs RTS coordinates. Then, the magnitudes of all position-discrepancy vectors were calculated, and the corresponding statistics were determined for both comparisons. Those statistics are presented in the 2nd and 4th column of Table 1. There, it is observed that the sample standard deviation (STD_S) of position discrepancies in the G-VA model are ≈ 4.2 times (0.046/0.011) larger than those in the G-TB model. This comparison of STD_S is visualized in Figure 3.

Distance Discrepancies

All 995 non-repeated distances, among all 45 sticker points, were calculated from within each of the 3 sets of position coordinates. This resulted in three groups of 995 distances each. Groups 1 and 2 contained distances within the G-TB and G-VA models, respectively. Group 3 had the distances measured in the field via the RTS instrument. With this data, two distance comparisons were performed: (i) distances from Group 3 (RTS) were subtracted from distances in Group 1 (G-TB model), and (ii) distances from Group 3 (RTS) were also subtracted from distances in Group 2 (G-VA model). This resulted in 995 distance discrepancies for each LiDAR model vs the same 995 distances measured via the RTS instrument. Figure 4 shows 995 distance discrepancies between the G-TB LiDAR Model and the RTS Instrument. Similarly, Figure 5 shows 995 distance discrepancies between the G-VA LiDAR Model and the RTS Instrument. The 3rd and 5th columns of Table 1 show the statistics of these discrepancies in distances. In those columns, it is observed that the STD_S of distance discrepancies in the G-VA model are ≈ 3.1 times (0.078/0.025) larger than those of the G-TB model. This comparison of STD_S is visualized in Figure 3. Figures 4 and 5 also show a trend line and the expressions of their corresponding linear regressions, along with their respective coefficients of determination (R^2 values). In the G-TB model, $R^2 \approx 0.3\%$ and in the G-VA model $R^2 \approx 12.2\%$.

Table 1

Statistics of discrepancies, G-TB model vs RTS, and G-VA model vs RTS: (a) Position discrepan-. cies of 45 sticker points. (b) Discrepancies in 995 non-repeated distances among those 45 points.

Statistic Function	G-TB LiDAR Model vs Robotic Total Station		G-VA LiDAR Model vs Robotic Total Station	
	(a) Position Discrepancies (US ft)	(b) Distance Discrepancies (US ft)	(a) Position Discrepancies (US ft)	(b) Distance Discrepancies (US ft)
Max =	0.051	0.080	0.194	0.251
Min =	0.008	-0.057	0.007	-0.183
Mean =	0.029	0.004	0.089	0.053
Median =	0.028	0.004	0.095	0.048
STD_S =	0.011	0.025	0.046	0.078
RMSE =	0.031	0.025	0.099	0.095

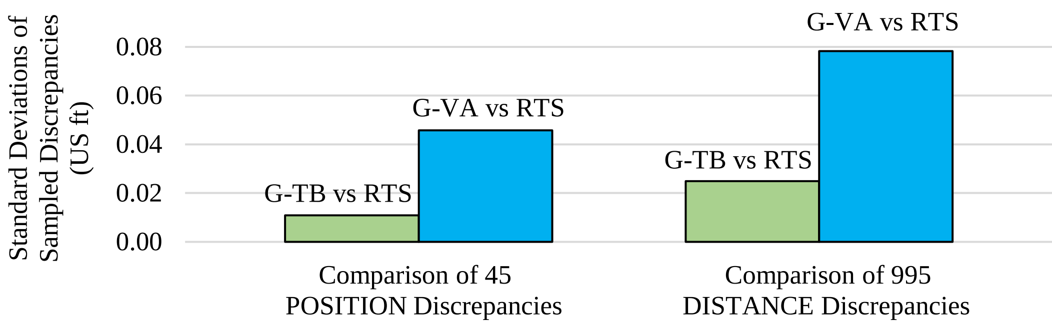


Figure 3: Discrepancies between each LiDAR Model (G-TB or G-VA) and RTS Instrument (US ft)

Confidence Levels and Intervals for the Attained Standard Deviations

The confidence level (CL), in percentage, for a standard deviation of samples (STD_S) is related to the limits of the confidence interval (CI) for that STD_S and depends on the number of samples (n). This study considered n=45 samples for sticker positions and n=995 samples for non-repeated distances among those 45 points.

Consequently, when analyzing the G-TB model, the 95% CL for the STD_S of its 45 position discrepancies is associated with a CI of [0.828*STD_S, 1.263*STD_S]. After substituting STD_S=0.011 ft, that CI becomes [0.009 ft, 0.014 ft]. On the other hand, the 95% CL for the STD_S of the 995 distance discrepancies is associated with a CI of [0.958*STD_S, 1.046*STD_S]. After substituting STD_S=0.025 ft, that CI becomes [0.024 ft, 0.026 ft]. Similarly, when considering the G-VA model, the 95% CL for the STD_S (0.046 ft) of its 45 position discrepancies is associated with a CI of [0.038 ft, 0.058 ft]. Additionally, the 95% CL for the STD_S of the 995 distance discrepancies (0.078 ft), is associated with a CI of [0.075 ft, 0.082 ft].

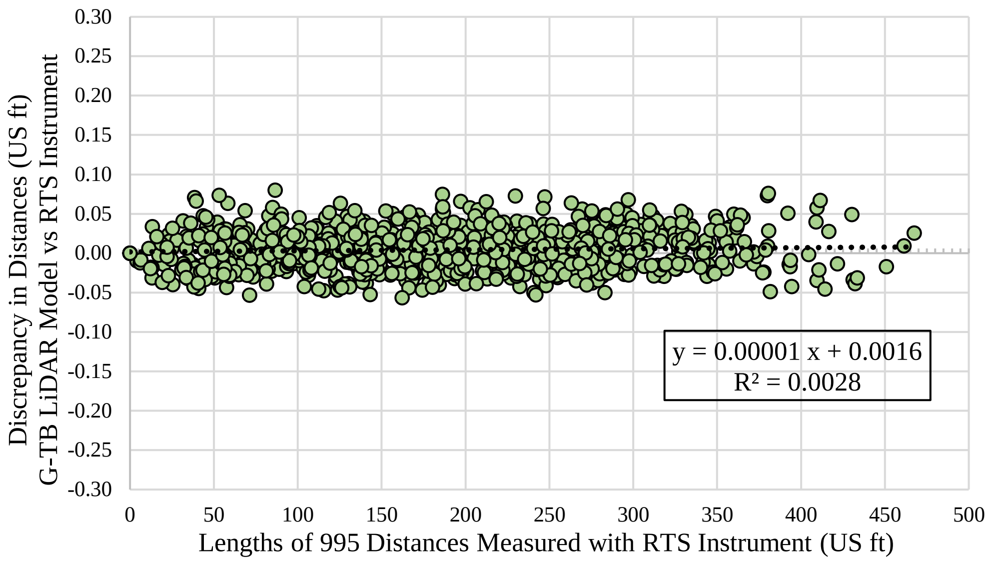


Figure 4: Distance Discrepancies between G-TB LiDAR Model and RTS Instrument (US ft)

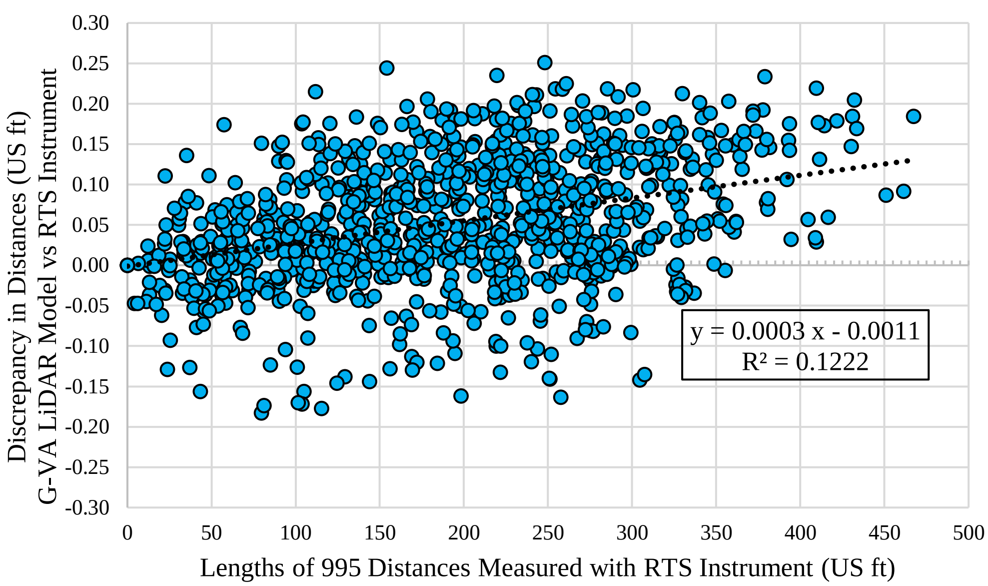


Figure 5: Distance Discrepancies between G-VA LiDAR Model and RTS Instrument (US ft)

Conclusions and Final Remarks

This work compared the relative accuracy of two Leica Geosystem's point-cloud registration methods, the Target-Based and Visual-Aligned ones. The latter is a computer-assisted version of the Cloud-to-Cloud approach. They both are popular techniques, employed by users of Leica's scanners, to stitch point clouds. Results indicate that, in this case study, after modeling a 3.5-acre site, with 34 scans, along a closed loop, the TB registration is more accurate than the VA registration. After determining the position of 45 points, the G-TB model is ~4.2 times more accurate, in a one-standard-deviation sense (1-σ sense), than the G-VA model. Similarly, after determining 995 distances (ranging from ~0 ft to ~460 ft), the G-TB model is ~3.1 times more accurate, in a 1-σ sense, than the G-VA model. This can be observed in figures 3, 4 and 5. These differences could be due to lack of enough overlapping between pairs of neighboring scans. The successive scans were completed following a closed loop around the main buildings, and registration errors could accumulate more rapidly in the VA approach because it stitches two neighboring scans at a time, not all of them together, as in the TB scheme. In fact, the first completed loop resulted in a clearly visible closing error for the VA method. That error was reduced by including extra scans (for a total of 34). This increased the overlapping of neighboring pairs with initial low superposition. This has prompted the authors to complete 2 similar experiments to complement the current study. It is noticed that, in the 2 new case studies, the discrepancies between the TB and VA registration methods are negligible. However, each of the 2 new experiments cover smaller areas, 1 acre each instead of 3.5, only involve 6 scans, rather than 34, and each scan is well overlapped with the remaining 5. The smaller size and the higher overlapping conditions could be contributing to those negligible discrepancies between both registration approaches. This will the subject of future studies.

References

Cosarca, C., Jocea, A., and Savu, A. (2009). Analysis of error sources in terrestrial laser scanning. *Journal of Geodesy and Cadastre*, 11, 115-124.

U.S. Geological Survey. (1998). Federal Geographic Data Committee Part 3: *National Standard for Spatial Data Accuracy*, FGDC-STD-007.3: Washington, D.C.

Kassler, M. (2021, February 24). C2C vs Target Based Registration. Laser Scanning Forum. https://www.laserscanningforum.com/forum/viewtopic.php?t=17478

Leica Geosystems (2010), Leica ScanStation C10, User and System Field Manuals, Version 1.0.

Maldonado, G., Usman, I., Purcell, R., Nam, S., and Maghiar, M. (2022). Distance discrepancies in T-LiDAR, Point-Cloud Models Georeferenced via RTK and Static GNSS. ASC 2022 58th Annual ASC International Conference, *Epic Series in Built Environment*, 3, 434-442.

Muralikrishnan, B. (2021). Performance evaluation of terrestrial laser scanners–a review. *Measurement Science and Technology*, 32, 072001.

Ogawa, T., and Hori, Y. (2019). Comparison with accuracy of Terrestrial Laser Scanner by Using Point Cloud Aligned with Shape Matching and Best Fitting Methods. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLII-2/W9, 535-541.

Rajendra, Y. D., Mehrotra, S. C., Kale, K. V., Manza, R. R., Dhumal, R. K., Nagne, A. D., and Vibhute, A. D. (2014). Evaluation of partially overlapping 3D point cloud's registration by using ICP variant and CloudCompare. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences,* XL-8, 891-897.

Walsh, G., (2015). Leica ScanStation P-Series- Details that Matter. Leica Geosystems AG, Switzerland. https://blog.hexagongeosystems.com/wp-content/uploads/2015/12/Leica_ScanStation_P-Series_details_that_matter_white_paper_en-4.pdf