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Distance Discrepancies in T-LiDAR, Point-Cloud Models Georeferenced via RTK and Static GNSS

Gustavo Maldonado, Ph.D., PE, Usman Ibrahim, M.S., Roger C. Purcell, Ph.D., PE, RLS, Soonkie Nam, Ph.D., and Marcel Maghiar, Ph.D., CM-BIM
Georgia Southern University
Statesboro, Georgia, USA

This article analyzes two virtual 3D point-cloud models, generated via terrestrial light detection and ranging (T-LiDAR), to compare the relative inaccuracies in distances introduced by two different georeferencing approaches. One is rapid (~30 seconds per ground point) and commonly used in practice, the Real-Time, Kinematic (RTK) Global Navigation Satellite System (GNSS) approach, and the other is a more accurate, but time consuming (4 hours per ground point), Static GNSS scheme. The goal is to determine statistical length discrepancies in the same distances extracted from two differently georeferenced 3D models of the same spatial geometry. Currently, this type of comparison is not readily available to practitioners and could assist in selecting the type of GNSS-based georeferencing procedure. The modeled area encompasses ~30,000 ft^2 of a university campus and includes the exterior portion of a building. To determine the discrepancy in measured distances from the two differently georeferenced models, the same one hundred points were identified simultaneously in each of them, and the same 600+ distances were virtually extracted from each model. Then, the discrepancy of each pair of corresponding distances was calculated and its statistics were determined. A full analysis of those discrepancies is presented in this article.

Key Words: Georeferencing, GNSS, LiDAR, Distance Discrepancy

Introduction

Laser-based terrestrial scanners become commercially available in the mid-1990s and evolved significantly in the last 25 years (Gaurav, 2018). Today, the latest devices and their associated software packages are faster, more powerful, and more affordable. This has contributed to their current ubiquity in the Architecture, Engineering and Construction (AEC) industry. The resulting models capture existing spatial conditions (i.e., topography and/or built environments) and are employed for various purposes, including virtual surveying, predesign/design processes, monitoring of construction progress, determination of pay quantities, capture of as-built conditions, etc. Even though manufacturers disclose the accuracies of their respective laser scanning devices, it is still necessary to study the resulting accuracies under real field conditions and after implementing certain postprocessing tasks that may affect those accuracies, such as the georeferencing of the final point-cloud models. According to

Boehler et al (2003), "The accuracy specifications given by laser scanner producers in their publications and pamphlets should always be doubted." Several studies have analyzed those accuracies, including the work of Maldonado et al. (2020) where the discrepancy between georeferenced and non-georeferenced models were investigated. Additionally, Maldonado et al. (2021) estimated the error introduced by georeferencing a point-cloud model via an accurate closed-traverse survey. These two articles include more extensive literature reviews on this topic.

The goal of this study is to determine statistical length discrepancies in pairs of same distances extracted from two T-LiDAR, point-cloud models of the same spatial geometry, shown in Figure 1 (a). Each model is georeferenced by a different GNSS-based technique: (i) A rapid RTK GNSS approach and (ii) a more accurate, but slower, Static GNSS approach. The objective is to quantify statistical differences in lengths caused by the rapid georeferencing approach with respect to the more accurate, but slower static, alternative technique.

Instruments and Methodology

This study employed two instruments from Leica Geosystems. They are the ScanStation C10 and the Viva GS14 GNSS Smart Antenna device, with its CS10 handheld controller, as shown in Figure 2. The scanner was used to generate a non-georeferenced point-cloud model of a selected area (~3330 yd^2 ≈ 30,000 ft^2). The manufacturer (Leica 2021a) indicates that the C10 scanner has position accuracy of 6 mm (0.24 in) and measurement accuracy of 4 mm (0.16 in), both are 1σ at 1m-50m range. This scanner contains a dual-axis compensator with horizontal and vertical angular accuracies of 12 seconds. Its scanning range is 300 m (328 yd) at 90% albedo and 134 m (146.5 yd) at 18% albedo. The maximum scanning rate is 50,000 points per second. The Viva GS14 GNSS antenna has a maximum position update rate of 20 Hz and can track various constellations of satellites (GPS, GLONASS, BeiDou, Galileo and SBAS). However, this study only employed the GPS and GLONASS constellations. According to Leica Geosystems (Leica 2021b), the GS14 device has different horizontal (Hz) and vertical (V) position accuracies, depending on the employed technique. For a network-based, rapid RTK approach, the position accuracies are Hz 8mm+0.5ppm and V 15mm+0.5ppm (Hz 0.31in+0.5ppm and V 0.59in+0.5ppm). For long static individual observations, requiring post-processing, the indicated accuracies are Hz 3mm+0.1ppm and V 3.5mm+0.4ppm (Hz 0.13in+0.1ppm and V 0.14in+0.4ppm). Additionally, for this GNSS device, Leica indicates "Measurement precision, accuracy, reliability and time for initialization are dependent upon various factors including number of satellites, observation time, atmospheric conditions, multipath, etc. Figures quoted assume normal to favorable conditions."

The modeled area includes the West exterior portion of the Engineering Building and its surrounding garden, at the Statesboro Campus of Georgia Southern University (see Figure 1). Approximately, it encompasses an open space of 30,000 ft^2. The completion of this project involved four main tasks: (i) Data collection in the field, via the C10 and GS14 instruments. (ii) Postprocessing of the scanned data in the BEaM laboratory using the Leica Cyclone software. It consisted in the removal of noise (i.e., pedestrian traffic) and in the registration (stitching) of all scans. (iii) Postprocessing of georeferencing position data via the Online Positioning User Service (OPUS) of the National Geodetic Survey (NGS). (iv) Statistical analysis of the discrepancies in the same distances extracted from each of the two models, RTK-Georef and Static-Georef, which were georeferenced using different approaches.

(a) (b)

Figure 1. (a) Plan view of modeled area, marked in red, of Engineering Bldg. Picture from Google Maps, 2021. (b). Resulting Virtual, 3D, Point-Cloud Model (perspective view)

Before scanning, 100+ black-and-white, stickers (~10cm×10cm each) were attached at different locations on the walls, columns, window frames, and other features within the modeled area. This was done to properly capture and identify the same100 points in the two distinctly georeferenced models.

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

Figure 2. Employed devices and targets. (a) Leica's ScanStation C10, (b) & (c) Leica's GS14 GNSS Smart Antenna. (d) White, Six-Inch, Spherical Target. (e) Captured B&W Sticker Target

During field operations, a total of thirteen (13) exterior scans were completed to cover the selected area. This took approximately 35-45 minutes per scanning station. In this study, we adopted the target-based registration (stitching) process to build the initial, non-georeferenced model. Therefore, various white, spherical, six-inch diameter targets (see Figure 2 d) were employed to serve as connecting points while registering (stitching) the different scans into a common system of reference. Before georeferencing the model, the selected system of reference is arbitrary. This system coincides with the reference frame of the first scan listed in the stitching group. To properly register two neighboring scans, it is necessary that they both contain at least 3 common targets. This target-based registration was adopted since it is more accurate than the other two available techniques in Leica's Cyclone software, the cloud-to-cloud, and the visual-alignment registrations. However, the adopted target-to-target approach required additional time in the field for target acquisition. One-foot-long steel nails were employed to materialize the ground points where the spherical targets were placed, on top of aluminum poles. Four of those ground points (TP1, TP3, TP5, and TP8) were selected as ground control points for georeferencing purposes. The spherical targets were preferred because, unlike plane-circular targets, they can be acquired from different angles without the need of human intervention to rotate them toward the different scanning stations. This minimizes potential errors introduced during that reorientation process.

The coordinates of four fixed ground control points were acquired in the Georgia-East State Plane Coordinate System (GA-E SPCS), to georeference the resulting point-cloud model. First, those coordinates were obtained via a rapid RTK GNSS approach. For this, the GS14 antenna served as a rover connected via Wi-Fi (provided by an Android-based cellular phone) to the Internet to access the privately owned eGPS Network of fixed bases, in Georgia and Alabama. It took approximately 20-30 seconds to obtain these RTK coordinates for each of the 4 ground control points. Then, these coordinates were employed to georeference the previously generated, fully stitched, 3D point-cloud model. The resulting georeferenced model is herein referred to as the *RTK-Georef* model. Second, the coordinates of the same four ground control points were acquired via a slower, but more accurate, long Static GNSS approach. For this, 4 hours of continuous position data acquisition was completed at each of the 4 ground control points. This data was submitted to OPUS for processing and correction. The 4 hours of continuous data acquisition was selected to assure close approximation to the most accurate position values attainable with the GS14 GNSS device via OPUS processing. In this regard, information available at OPUS' website (OPUS, 2021) shows two convergence graphs, one for horizontal and one for vertical positioning coordinates, extracted from Gillis et al (2019). Those graphs show that 4 hours of continuous data acquisition almost attain convergence in the horizontal and vertical positions (with a root mean square error of ~10 mm ≈ 0.4 in). The georeferenced model resulting from these, more accurate, coordinates is herein referred to as the *Static-Georef* model. Table 1 shows the GA-E SPCS coordinates of the four ground control points acquired by these two GNSS approaches.

Table 1

Coordinates of Ground Control Points and their Discrepancies

Fixed Ground Control Points	RTK-GNSS COORDINATES (GA E SPCS)			STATIC-GNSS COORDINATES (GA E SPCS)			DISCREPANCY in COORDINATES			MAGNITUDE of DISCREPANCY VECTOR	
	North (US foot)	East (US foot)	Elev. (US foot)	North (US foot)	East (US foot)	Elev. (US foot)	North (inch)	East (inch)	Elev. (inch)	(inch)	(mm)
TP1	881054.443	773544.654	211.652	881054.567	773544.627	211.532	-1.49	0.32	1.44	2.10	53
TP3	881057.605	773510.552	210.672	881057.736	773510.507	210.387	-1.57	0.54	3.42	3.80	97
TP5	880931.134	773662.035	211.321	880931.243	773662.019	211.276	-1.31	0.19	0.54	1.43	36
TP8	880940.019	773553.334	207.201	880940.089	773553.309	207.142	-0.84	0.30	0.71	1.14	29
				Magnitude of Averaged Discrepancy Vector					→	**2.12**	**54**

After the two distinct RTK-Georef and Static-Georef models were generated, 100 virtual pairs of points were identified in them. Each pair contained the coordinates of the same point but extracted from different georef models. That is, each point in each pair presented slightly different coordinate values. Additionally, 7 points were randomly selected from the original 100 to server as center points (CPs) in each georef model. Virtual distances were measured from each of these CPs to the remaining 99 points in each model. This resulted in numerous pairs of 2 corresponding virtual distances, each from a different georef model. Repeated distances were removed, so they did not weigh more than once in the calculated statistics. The total number of non-repeated distances in each model was 672. They ranged from near 0 to about 180 ft. However, it was inferred that a few of these distances involved points that contained erroneously acquired coordinates. These errors could have occurred when participating assistants manually extracted 600 numbers (3 coordinate components per point per model). That is, either the actual coordinates were wrongly recorded, or different, nearby points were wrongly considered as the same point in both point-cloud models. Those erroneous points and their defined distances are referred to as outliers. All local statistics (for distances from each center point) and global statistics (for all distances involved in this study) were calculated with and without outliers. The final statistics of all distance discrepancies are presented in the following section of this article.

Results

The GNSS coordinates acquired for the 4 ground control points are presented in table 1. They are in US-Foot units, as customarily used in the GA-E SPCS. This table indicates that the magnitude of the discrepancy vectors, between the RTK and the Static coordinates, range from 1.14 in to 3.8 in, with an average of 2.12 in. These initial discrepancies in the coordinates of the control points are expected as the RTK-GNSS approach is less accurate than the long Static-GNSS one. This difference prompted the completion of this study to observe how it affects the lengths of virtual distances measured within models georeferenced with each distinct set of control coordinates.

The discrepancies in all non-repeated 672 distances, from all 7 CPs, are graphically depicted in Figure 3. They involve distances defined by all 100 virtual points, in the RTK-Georef and Static-Georef models, including the outlying points.

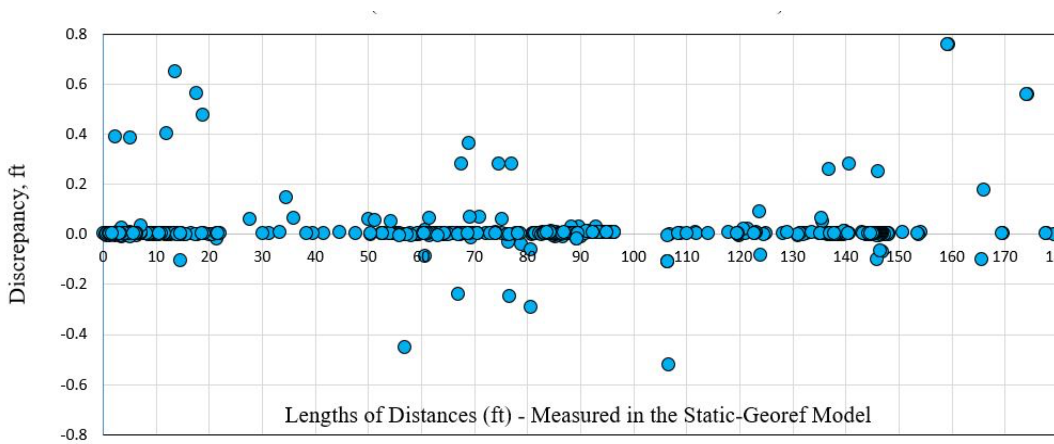

Figure 3. Discrepancies in 672 Measured Distances (**including outliers**)
RTK-Georef Model – Static-Georef Model

If the same set of control-point coordinates were employed to georeference both models, the extracted virtual distances, from each of them, would be the same, and their discrepancies would all be zero. Since the 4 control points were well distributed in the study area, and the largest position discrepancy between all 4 of them is 2.1 in + 3.8 in = 5.9 in ~ 0.49 ft (See TP1 and TP3 in table 1), it is inferred that 6 in = 0.5 ft is an appropriate estimate of the maximum discrepancy to be expected in all measured virtual distances in this study. However, Figure 3 shows a few discrepancy magnitudes (5 or 6) larger than 0.5 ft. This suggested that those distances were defined by outlying points, i.e., by points erroneously identified as the same one in the point clouds of both georef models, or by points with erroneously acquired/recorded coordinates from any of those models. This prompted the need to design and implement a two-component criterium to identify potential outliers:

{1} Individual Component: |Distance Discrepancy| must be ≥ 0.1 ft in 3 or more distances to CPs.
{2} Averaged Component: The averaged |Distance Discrepancy| to all 7 CPs must be ≥ 0.2 ft.

Criterion component {1} uses a relatively low 0.1-ft (i.e., 1.2-in) |Distance Discrepancy| threshold to assure that all potential outliers are considered. The selected 1.2-in level is just above the minimum discrepancy magnitude (1.14 in) shown by all 4 control points (see point TP8 in table 1). This criterion is satisfied only when that threshold is exceeded by the potential outlier in at least 3 distances to CPs, out of all 7 ones. Criterion component {2} uses a 0.2-ft (i.e., 2.4-in) threshold for the averaged discrepancy magnitudes of all 7 distances, from the potential outlier to the respective CPs. The 0.2-ft threshold was selected because it is just above the magnitude of the averaged discrepancy vector for all 4 ground control points, 2.12 in ≈ 0.177 ft ≈ 0.2 ft (see table 1). The application of these criteria is summarized in table 2 and resulted in the identification of only six outliers: Points: 3, 5, 6, 15, 31, & 62, out of the initially selected 100 points.

Table 2

Coordinates of Ground Control Points and their Discrepancies

Potential Outlier Point →	Points with |Discrepancy| ≥ 0.1 ft in Distance to Center Point							
	# 3	**# 5**	**# 6**	**# 15**	**# 20**	**# 31**	**# 62**	**# 65**
Center Points (CPs)	|Discrepancy| in Distance to Center Point (foot)							
1st (# 11)						0.363	0.522	
2nd (# 21)		0.279		0.561		0.383	0.454	
3rd (# 35)		0.281	0.249	0.473		0.389		
4th (# 50)		0.280	0.243	0.649		0.401		
5th (# 70)	0.249	0.278	0.259			0.291	0.146	0.107
6th (# 85)	0.558	0.176	0.755					0.110
7th (# 100)	0.559	0.101	0.755		0.101			0.109
# of Instances →	3	6	5	3	1	5	3	3
Magnitude range of each potential outlier (foot)	From 0.249 to 0.559	From 0.101 to 0.281	From 0.243 to 0.755	From 0.473 to 0.649	From 0.101 to 0.101	From 0.291 to 0.401	From 0.146 to 0.522	From 0.107 to 0.110
Averaged Discr. (ft) →	0.455	0.233	0.452	0.561	0.101	0.365	0.374	0.109
Identification Criteria:	# of Instances ≥ 3 AND Averaged Discr. ≥ 0.2 ft							
Identified Outliers →	**# 3**	**# 5**	**# 6**	**# 15**		**# 31**	**# 62**	

After removing the indicated 6 outliers, and their associated 42 distances, the remaining 94 points defined 630 non-repeated distances. The discrepancies of this reduced set are presented in Figure 4.

Discrepancies statistics were calculated for both groups, with and without outliers. They include Standard Deviations of the Population (STD P), Standard Deviations of the Sample (STD S), and Root Mean Square Values (RMSVs). These statistics were determined in a local sense, for each local set (considering only the radial distances to each CP), and in a global sense, for all involved distances in this study. Their summary is presented in table 3, where it is observed that all RMSVs approach the STDs. This is so because the mean values of the discrepancies in distances is almost equal to zero.

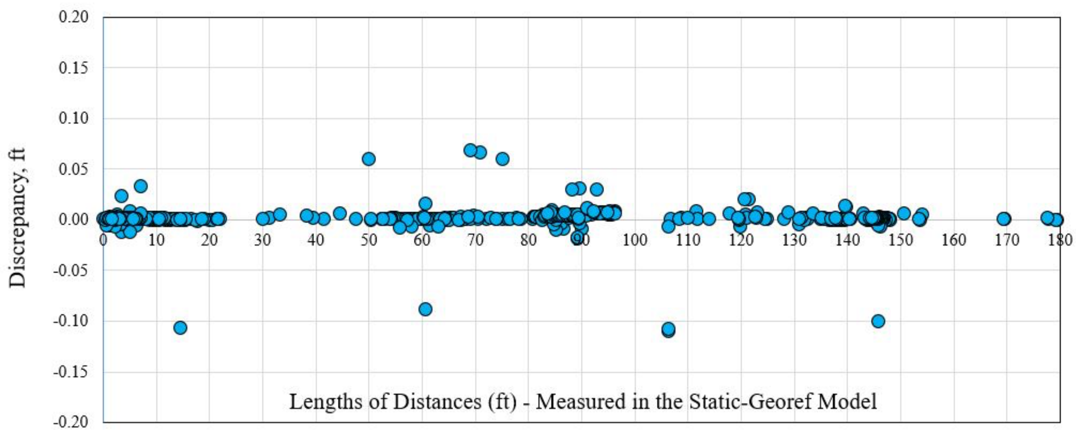

Figure 4. Discrepancies in 630 Measured Distances (**excluding outliers**)
RTK-Georef Model – Static-Georef Model

Table 3

Local and Global Statistics of Distance Discrepancies between the RTK- and the Static-Georef Models (With and Without Outliers)

Center Pts		With Outliers				Without Outliers				Diff., (With - Without)		
Local Set	#	# of Dist. in the Set	STD P Discrep (ft)	STD S Discrep (ft)	RMSV Discrep. (ft)	# of Dist. in the Set	STD P Discrep (ft)	STD S Discrep (ft)	RMSV Discrep. (ft)	Diff. in STD P Discr (ft)	Diff. in STD S Discr (ft)	Diff. in RMSV Discr (ft)
1st	11	99	0.065	0.065	0.065	93	0.007	0.007	0.007	0.058	0.058	0.058
2nd	21	98	0.087	0.088	0.088	92	0.008	0.008	0.008	0.079	0.080	0.080
3rd	35	97	0.073	0.073	0.074	91	0.008	0.008	0.008	0.065	0.065	0.066
4th	50	96	0.086	0.087	0.087	90	0.007	0.007	0.007	0.079	0.079	0.080
5th	70	95	0.058	0.059	0.059	89	0.013	0.013	0.013	0.046	0.046	0.046
6th	85	94	0.100	0.100	0.100	88	0.015	0.015	0.015	0.085	0.085	0.085
7th	100	93	0.099	0.100	0.100	87	0.016	0.016	0.016	0.083	0.084	0.084
		Total = 672				Total = 630						
		Local Ave	0.081	0.082	0.082	Local Ave	0.011	0.011	0.011	0.071	0.071	0.071
		Global #	0.083	0.083	**0.083**	Global #	0.011	0.011	**0.011**	0.071	0.071	0.072

Table 3 indicates that the removal of the 6 outliers caused a substantial decrement in all statistical values. This reduction is by a factor of 7.5, from ~0.083 ft (~1.0 in or ~25.3 mm) to ~0.011 ft (~0.13 in or 3.4 mm). To interpret the resulting statistics, the values corresponding to 1*σ (where σ is the STD of distance discrepancies), 2*σ and 3*σ were determined to assist in applying the 68-95-99.7 Empirical Rule. From the global statistics, σ = 0.083 ft for discrepancies with outliers, and σ = 0.011 ft for discrepancies without outliers. The corresponding values for the 1*σ, 2*σ, and 3*σ levels are shown in table 4, where it can be observed that 99.7% of the distance-discrepancy magnitudes are less than 5.99 inches (i.e., ≤ 151,9 mm) when including outliers, and less than 0.81 inches (i.e., ≤ 20.5 mm) when excluding outliers.

Table 4

68-95-99.7 Empirical Rule for ~Zero-Mean Normal Distribution

Level	With Outliers ft	With Outliers inch	With Outliers mm	Without Outliers ft	Without Outliers inch	Without Outliers mm	With Outliers Interval (in)	Without Outliers Interval (in)	Band width	With Outliers inch	Without Outliers inch	Included Population Percent
1*σ =	0.083	1.00	25.3	0.011	0.13	3.4	[-1.00, +1.00]	[-0.13, +0.13]	2*σ	1.99	0.27	68.3%
2*σ =	0.166	1.99	50.6	0.022	0.27	6.9	[-1.99, +1.99]	[-0.27, +0.27]	4*σ	3.99	0.54	95.5%
3*σ =	0.249	2.99	76.0	0.034	0.40	10.3	[-2.99, +2.99]	[-0.40, +0.40]	6*σ	5.98	0.81	99.7%

Summary, Final Remarks and Conclusions

This study compared numerous pairs of virtual distances (672 with outliers or 630 without outliers), ranging from ~0 to ~180 ft (i.e., to ~55m). They were measured among 100 virtual points in two 3D, T-LiDAR-based, point-cloud models. Each model encompassed the same spatial geometry but was georeferenced using different procedures. One employed a rapid RTK-GNSS approach and was designated as the RTK-Georef model. The other was georeferenced via a more accurate, but slower, Static-GNSS procedure and was referred to as the Static-Georef model. The considered distances were in 7 local groups, each with a central point (CP) randomly selected from the original 100 points. Each pair of virtual distances contained one length measured in the RTK-Georef model, and another length (slightly different) measured in the Static-Georef model. The overall standard deviation (STD=σ), or the almost equally valued, RMSV (≈ σ), of distance discrepancies between both models, is considered a measure of the overall relative error added to the final model by the less accurate RTK-based georeferencing approach. The σ value assists in the interpretation of the results by invoking the 68.3-95.5-99.7 Empirical Rule for Gaussian distributions. This rule indicates that the 2σ interval, [-σ, +σ], contains 68.3% of all measured discrepancies. Similarly, the six-sigma interval, [-3σ, +3σ], contains almost all, 99.7%, discrepancies. After analyzing the acquired virtual distances, it was suspected that the data may contain a few outlying points, possibly due to human errors during the identification of the exact same points in both virtual 3D models and/or during the acquisition and recording of coordinates from each model. This prompted the design and implementation of a procedure to attempt identifying those outliers. This resulted in the identification of 6 outlying points (out of 100) with their 42 associated distances (out of 672). After completion of the statistical analyses, with and without outliers, the following remarks and conclusions are presented:

1. The magnitude of the discrepancies in the position vectors of the 4 ground control points (due to RTK vs Static approaches) ranged from 1.14 in (~29 mm) to 3.80 in (~97 mm). Additionally, by adding the two maximum discrepancies associated to these 4 points (2.1 in + 3.8 in = 5.9 in ≈ 0.49 ft), it was initially inferred that the maximum expected discrepancy, among other distances, was close to that amount 5.9 in ~ 0.49 ft.
2. Regardless of including or excluding the outliers, the discrepancies in the lengths of all measured distances were almost equally distributed in the positive and negative sets of numbers. As expected, this resulted in an almost zero mean value for all calculated discrepancies. Consequently, as all mean values approached zero, all RMSVs approach their respective STDs.

3. The **local statistics** for the discrepancy of all 7 local sets of distances, including the 6 outliers, resulted in an averaged STD ≈ 0.082 ft (i.e., 25.0 mm). Excluding the 6 outliers, the averaged STD ≈ 0.011 ft (i.e., 3.4 mm).
4. The **global statistics** for the discrepancies of all distances, including the 6 outliers, resulted in STD ≈ 0.083 (i.e., 25.3 mm). Excluding the 6 outliers, the global STD ≈ 0.011 ft (i.e., 3.4 mm).
5. The exclusion of the 6 outliers (i.e., exclusion of their associated 42 distances) substantially reduced the STDs of both local and global statistics from ~0.0825 ft (i.e., 25.15 mm) to ~0.011 ft (i.e., 3.4 mm). In both cases, the reduction factor is 7.5.
6. According to the Empirical Rule, considering all points, including outliers, 99.7% of all distances should have |Discrepancy| ≤ 5.98 in (i.e., ≤ 151.9 mm). However, after excluding outliers, 99.7% of all remaining distances should have |Discrepancy| ≤ 0.81 in (i.e., ≤ 20.6 mm).
7. The previous point suggests that the statistics including the outliers are more closely related to the initially expected maximum discrepancy of 5.9 in (see point 1) than the statistics excluding the outliers. This could imply that the actual outliers should have been less than 6, or none. In turn, this prompts to a future new analysis where only 4 outliers are kept (points #3, #6, #15 and #62). That is, if the points associated with |Discrepancy| ≥ 0.5 ft are identified as the only outliers, investigate how this will affect the resulting statistics.

References

Boehler, W., Bordas Vicent, M., & Marbs, A. (2003). Investigating laser scanner accuracy. ISPRS - *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XXXIV (5)/W15, 696-701.

Gaurav, S. G. (2018). Brief History of LiDAR, Its Evolution and Market Definition. *BCC Research Editorial*, March 20, 2018. https://blog.bccresearch.com/brief-history-of-lidar-evolution-and-market-definition. Accessed on November 14, 2021.

Gillins, D.T. Kerr, D., and Weaver, B. (2019). Evaluation of the Online Positioning User Service for Processing Static GPS Surveys: OPUS-Projects, OPUS-S, OPUS-Net, and OPUS-RS. *Journal of Surveying Engineering, American Society of Civil Engineers*, Vol. 145, Issue 3.

Leica ScanStation C10 Data Sheet (2021a), Leica ScanStation C10. The All-in-One Laser Scanner for Any Application. Available at the below link, accessed on Nov 14, 2021: https://lib.store.yahoo.net/lib/yhst-141816440267150/Leica-ScanStation-C10-DataSheet.pdf

Leica Viva GS14 Data Sheet (2021b), Available at the below link, accessed on Nov 14, 2021: https://www.mainetechnical.com/mc_files/2/Leica_Viva_GS14_DS_us.pdf

Maldonado, G.O., Maghiar, M., Tharp, B., and Patel, D., (2020). Point-Cloud Models of Historic Barns – Spatial Discrepancies of Laser Scanning versus Robotic Total Station. ASC 2020 56th Annual ASC International Conference, (Epic Series in Built Environment, vol 1), pp 292-300.

Maldonado, G.O., Maghiar, M., and Augustine, A., (2021). Comparison of Distance Discrepancies in Georeferenced and Non-Georeferenced Terrestrial LiDAR Models. ASC 2021 57th Annual ASC International Conference, (Epic Series in Built Environment, vol 2), pp 311-319.

OPUS: Online Positioning User Service, *National Geodetic Survey*. Available at the following website: https://geodesy.noaa.gov/OPUS/about.jsp. Accessed on November 14, 2021.