Interlaboratory Study on Precision Statement of Using a Terrestrial Laser Scanner to Verify Concrete Tolerance

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This article covers a study designed to revisit an ongoing debate regarding the use of three-dimensional (3-D) laser scanners for evaluating concrete construction tolerances. Scanner hardware and software, as well as general practices, continue to evolve, so how has this progress affected the accuracy of scan measurements?

Starting as early as the mid-2010s, laser scanners have been used to evaluate floor flatness and levelness as well as the accuracy of built structures. A 2018 World of Concrete workshop on laser scanners led to a call for action: a jobsite laser scanning study was needed to validate the accuracy, repeatability, and reproducibility of this class of tools. A study plan was subsequently developed to determine if laser scanners had the technical capability to evaluate horizontal and vertical tolerances as specified in ACI SPEC-117-10(15)[1] as well as provide data suitable for determining floor flatness F_F and floor levelness F_L per ASTM E1155/E1155M.[2]

The results were published in two *Concrete International* articles.[3,4] Based upon the overall capabilities of the eight participants, the authors of Reference 3 concluded that "it would be appropriate to use a laser scanner for specification compliance when measuring a vertical tolerance of 5/8 in. (15.9 mm) or more and a horizontal tolerance of 1 in. [25.4 mm] or more." However, an examination of the tabulated data shows that three of the participants were able to achieve much better results than the overall group, both in terms of improved accuracy compared to a total station as well as smaller standard deviations. Could their results be more broadly achieved today? Let's find out.

Laser Scanning Background

Laser scanning technology, now ubiquitous in fields ranging from archaeology to medicine, has a fascinating history rooted in the innovative spirit of the twentieth century. While its origins can be traced back to the 1960s, it wasn't until the late 1990s that laser scanning truly began to revolutionize how people capture and interact with the world.

Early attempts at laser scanning were rudimentary, involving lights, projectors, and cameras to capture surface data. These systems were slow, cumbersome, and lacked the accuracy of modern technology. However, the development of LiDAR (light detection and ranging) in 1985 marked a significant turning point. By using laser pulses to measure distances, LiDAR enabled faster and more accurate 3-D data capture.

The late 1990s saw laser scanning gain popularity in engineering and surveying, thanks in large part to the groundbreaking Cyrax scanner developed by Cyra Technologies. This portable scanner paved the way for wider adoption of the technology. The 2000s brought further advancements with the introduction of 360-degree scanners and significant improvements in speed, accuracy, and portability.

A spectrum of scanning methods

Today, laser scanning encompasses a variety of techniques, each with its own strengths and applications:

- **Terrestrial Laser Scanning (TLS)**—Often referred to as ground-based LiDAR, TLS involves setting up a scanner on a tripod to capture highly accurate 3-D data of surrounding environments. This method is widely used in surveying, construction, and architectural documentation;

- **Mobile Laser Scanning (MLS)**—MLS systems are mounted on vehicles, enabling rapid data collection over large areas. This is particularly useful for mapping roads, railways, and infrastructure;
- **Airborne Laser Scanning (ALS)**—Mounted on aircraft or drones, ALS systems capture data from above, making them ideal for large-scale mapping, forestry management, and aerial surveys; and
- **Simultaneous Localization and Mapping (SLAM)**—SLAM technology allows scanners to map an environment while simultaneously determining their location within that environment. This is particularly useful for indoor mapping and robotic navigation.

This diverse range of scanning methods has broadened the applications of laser scanning, making it an essential tool for numerous industries.

Building the future—Laser scanning in construction

One of the most impactful applications of laser scanning lies within the construction industry. Here, it's transforming workflows and improving efficiency at every stage of a project's life cycle:

- **Pre-construction**—Laser scanning allows for the creation of highly accurate 3-D models of existing sites, providing crucial information for planning and design. This helps identify potential clashes or challenges before construction begins, reducing costly rework;
- **Construction monitoring**—By regularly scanning a site during construction, progress can be tracked against the original design. This helps identify any deviations early on, ensuring that the project stays on schedule and within budget;
- **Quality control**—Laser scanning enables precise measurements and comparisons, ensuring that construction adheres to quality standards and specifications. This minimizes errors and reduces the need for redesign; and
- **As-built documentation**—Upon project completion, laser scanning provides a comprehensive and accurate record of the as-built structure. This valuable documentation can be used for facility management, renovations, and future expansions.

Specific examples of laser scanning in action include:

- **Renovation and restoration**—Laser scanning is invaluable for projects involving existing structures, especially historical buildings. It allows for the creation of detailed digital models that capture intricate architectural features, aiding in preservation efforts and ensuring accurate restoration;
- **Safety exclusion zones, environmental sensitivity, and emergency response**—The scanned context of a proposed building will identify overhead power lines, fire hydrants, mature trees, and storm inlets. Location of power lines and emergency service points will help inform crane setup and site logistics. Mature trees that will be preserved through construction and storm drains also affect concrete pumping and concrete truck washout planning;
- **Mechanical, electrical, and plumbing (MEP) coordination**—Laser scanning helps identify potential clashes between MEP systems and structural elements, streamlining coordination and preventing costly on-site conflicts;
- **Structural analysis**—Scan data can be used to assess the structural integrity of buildings and infrastructure, identifying areas of concern and facilitating maintenance or repair work; and
- **Prefabrication**—Laser scanning supports the growing trend of prefabrication by enabling precise measurements and digital models that ensure accurate fabrication of components off-site.

Study Scope

Design

This study was designed to comply with ASTM E691-23, "Standard Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method."[5] The focus was on the application of TLS systems, as TLS is widely acknowledged to be the most precise and accurate scanning technique and has been widely adopted to verify dimensions and locations on construction projects. The objectives were to determine the precision, repeatability, and reproducibility of TLS technology when used to verify that constructed concrete elements are within specified tolerances; to provide a bias estimate; to update the conclusions from the previously mentioned study; and to provide insights on factors that could introduce errors in tolerance compliance results. It should be noted that this study was designed to assess the performance of TLS technology on a construction jobsite, rather than in a controlled environment. This study was not intended to reassess the suitability of laser scanning for the F-number system. Further, the study was not designed to compare hardware or software systems.

Participants and testing area

This study involved 13 participants from various regions across the United States (ASTM E691-23 states that a minimum of six "laboratories" must participate in a study, and it recommends that at least eight are engaged to allow for attrition). The participants volunteered to conduct the testing on a construction site in Santa Cruz, CA, USA, on July 27-28, 2024 (Table 1). The testing area was on Level 2 Pour Area 1 of a building being constructed by The Conco Companies. This level consisted of a post-tensioned (PT) slab that had been placed on July 16 and stressed on July 24. The PT slab formwork remained in place under the test area so the structural dead load would not affect the slab edge or slab opening target locations. The testing area also included columns that were cast on July 23 and shotcrete walls that were placed on July 22. The testing area was cleared for access and safety (Fig. 1).

The participants included contractors, surveyors, service providers, and representatives of scanner manufacturers.

Table 1:
Construction site testing of various TLS equipment

Participant	Role	Region	Hardware	Registration software	Scan setups (1st/2nd)	Experience, years
1	Service provider	Northeast	FARO Premium 70	FARO SCENE 2023.1	20/18	10 to 15
2	Contractor	Southwest	Leica RTC360	Leica Cyclone Register360 V2024.0.1	11/12	15+
3	Contractor	Southwest	FARO Focus Premium 350	FARO SCENE	16/17	10 to 15
4	Manufacturer	Southeast	FARO Focus Premium 350m	FARO Scene 2023.1 and 2024	17/13	Less than 5
5	Contractor	Southwest	Leica RTC360	Leica Cyclone Register360 Plus	12/11	5 to 10
6	Service provider	Northwest			7/6	10 to 15
7	Manufacturer	Midwest			12/10	5 to 10
8	Contractor	Northeast			8/10	Less than 5
9	Surveyor	Southwest	Leica P50	Leica Cyclone	6/5	10 to 15
10	Manufacturer	Rocky Mountain	Trimble X9	FieldLink and Realworks	8/8	5 to 10
11	Surveyor	Southwest		Trimble Realworks	9/8	10 to 15
12	Contractor	Northwest	Leica RTC360	Leica Cyclone Register360 Plus	7/6	10 to 15
13	Manufacturer	Northeast	Z+F Imager 5016	Z+F LaserControl	7/7	15+

Fig. 1: Testing area, participants, and their TLS instruments (partial)

While the organizers did not rigorously screen the participants, all the participants were self-qualified to conduct the test with extensive experience in laser scanning. Prior to the testing, two virtual meetings were hosted to help the participants understand the testing tasks and plan the survey accordingly. They were also asked to check and adjust the scanners before the field effort. Then during the test, each participant was given sufficient time to properly operate the equipment.

Testing material

"Testing material" consisted of 19 checkpoints, which were either 6 in. (152 mm) black and white (B/W) targets printed on sheets of uncoated, 100 lb paper and affixed to concrete surfaces using a spray adhesive (Fig. 2) or the intersections of fine chalk lines (Fig. 3). Checkpoints 200 to 205 consisted of B/W paper targets on vertical concrete surfaces. Checkpoints 100 to 103 consisted of B/W paper targets on the slab surface, with a 6 in. offset from the slab edge. Checkpoints 300 to 308 consisted of six chalk lines snapped on the surface of a concrete wall to form nine intersection points. The testing material also included 12 control points (CP1 through CP12), which consisted of B/W paddle targets (Fig. 4). Refer to Fig. 5 for a detailed plan of the target distribution.

The positions of the checkpoints and control points were established and independently surveyed by two licensed survey crews (from BKF and KW) and two field engineering crews (from Conco and K&K). Two crews also completed a close-out survey of the control targets to confirm the targets were not disturbed during the 2-day testing period. Least square adjustments were performed on the surveyed points, and final values were agreed upon by the four survey crews.

Fig. 2: One of the black and white (B/W) paper targets used during testing

Fig. 3: Concrete wall with fine chalk lines

Fig. 4: The control points consisted of B/W paddle targets designed to be rotated around the center axes for line-of-sight measurements

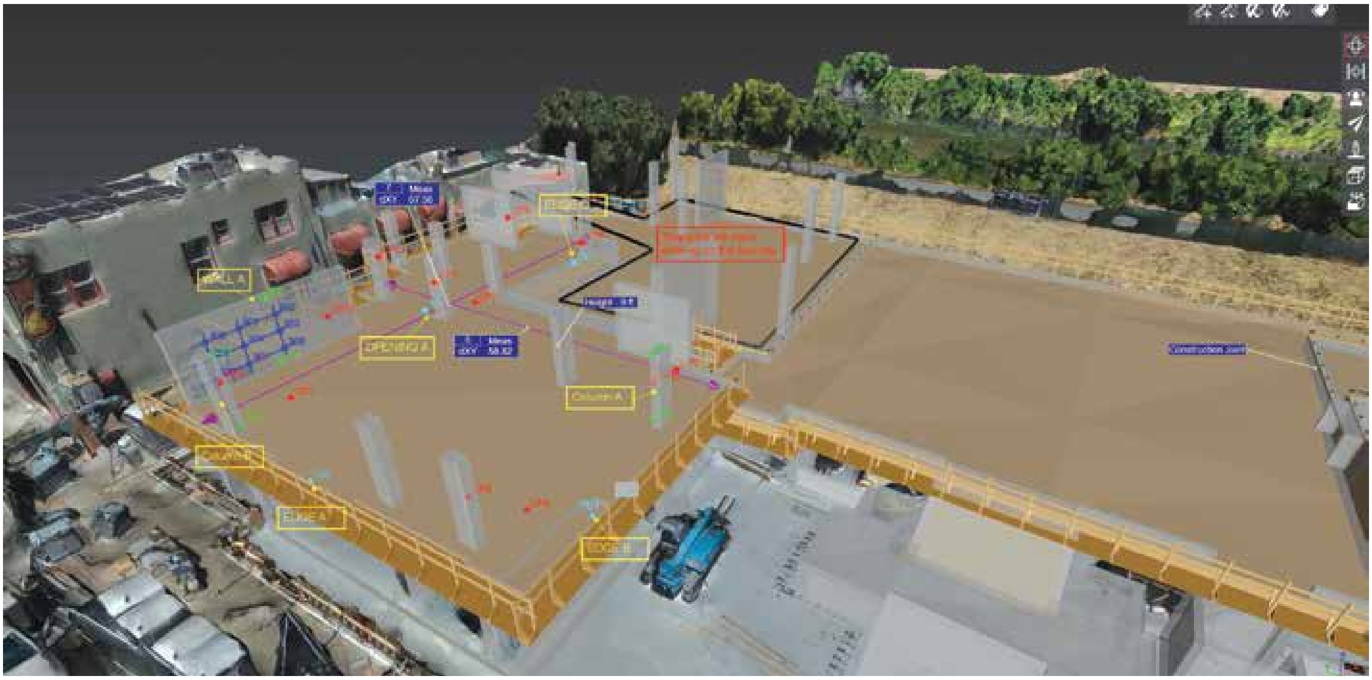


Fig. 5: Plan of target distribution: four control points CP1-4 on slab + eight control points CP5-12 on vertical surfaces; four B/W paper targets on slab edge (100 to 103); four B/W paper targets on column face (200 to 203); two B/W paper targets on wall face (204, 205); and six clear chalk lines on the wall face forming nine intersection points (300 to 308)

The coordinates of the control points were distributed to the scanning participants in a csv format (Point ID, Northing, Easting, Elevation) by email. Participants were asked to determine Northing (Y), Easting (X), and Elevation (Z) coordinates for the 19 checkpoints, using as many of the 12 control points as they deemed necessary for registration (geo-referencing) during post-processing of the point clouds generated by their scanners.

Testing activities

A pre-testing reception and meeting sponsored by the ASCC Foundation was held on July 26, 2024, the day before Test Day 1, to ensure all participants were familiar with the mission and to distribute files necessary for communicating their results. These files included a Revit model, a two-dimensional (2-D) CAD model, two formatted Excel data sheets, and a survey. The Revit and CAD models provided design locations for the points in the testing area, and they shared the same origin as the control points on the testing site. Excel sheet B.1 was formatted for inputting Northing, Easting, and Elevation values on the checkpoints. Excel sheet B.2 was formatted for inputting the distance deviation values compared to the design locations for Column A, Column B, Wall A, Edge A, Edge B, Edge C, and Opening A (Fig. 5). The survey included questions regarding data collection and registration files for future study. Participants were also asked to provide ASTM E57[5] data exchange files for their scans. These files will be used by the authors in a follow-up analysis.

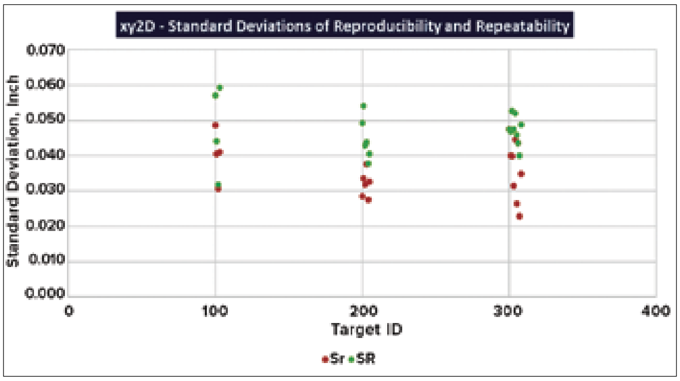
Each participant performed scans twice over the weekend to meet the minimum requirement for a repeatability study, and each participant applied their own best practices and workflow individually (they were free to select the TLS setup points and scan densities they deemed necessary to establish setup positions).

Data Analysis

Part 1a — Precision statement

This study includes 10 paper targets and nine chalk-line intersections, collectively referred to as "targets" in the context below. Nineteen target x, y, and z coordinates from each participant on both days were arranged in rows and columns in a spreadsheet (B.1). Two participants were unable to provide chalk-line intersection coordinates due to scanning setup parameters and photo capturing limitations that prevented the intersections from being visible in the point cloud data. Additionally, one participant was unable to return coordinates for checkpoint 101 due to data capturing and line-of-sight limitations. The total returned values are 456 counts for each coordinate x, y, and z. Each target coordinate (x, y, and z) exists in 3-D space. The vector magnitude on the 2-D plane was calculated using the square root of the sum of the squares of x and y coordinates, and the vector magnitude in 3-D was calculated using the square root of the sum of the squares of x, y, and z coordinates; 2-D and 3-D values were included in the same spreadsheet. Then, cell statistics were calculated per ASTM E691-23, Section 15.4,[5] which provided the cell average, cell deviation, *h*-value between-laboratory consistency, and *k*-value within-laboratory consistency of test results of the participant. Next, precision statistics were calculated per ASTM E691-23, Sections 15.5 and 15.6, which provide the repeatability standard deviation and reproducibility standard deviation (Fig. 6). Meanwhile, consistency statistics *h* and *k* were calculated per ASTM E691-23, Section 15.7, and *h*-value and *k*-value graphs were provided (Fig. 7). The *h* and *k* graphs provide an overall picture of the variability of the results as well as single out the outliers to be investigated. In this study, a significance level of 1.0% was chosen for the *h* and *k* analysis, as the data judgment suggested that using a higher significance level would not result in an excessive number of outliers. The results showed that four targets from participants 3, 10, and 13 fell outside the 2.41 critical value in the *h* study, while two targets from participants 3 and 8 fell outside the 2.54 critical value in the *k* study. These six outliers were investigated and deemed not significant enough to be excluded from the analysis. Therefore, all data were retained for the precision statement analysis and bias estimation.

The repeatability standard deviation (Sr) and reproducibility standard deviation (SR) for each target are



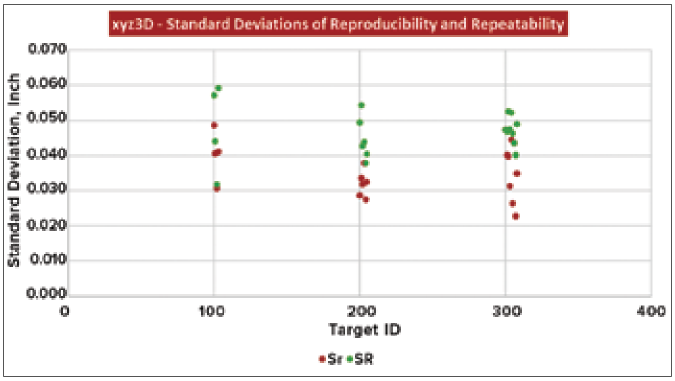
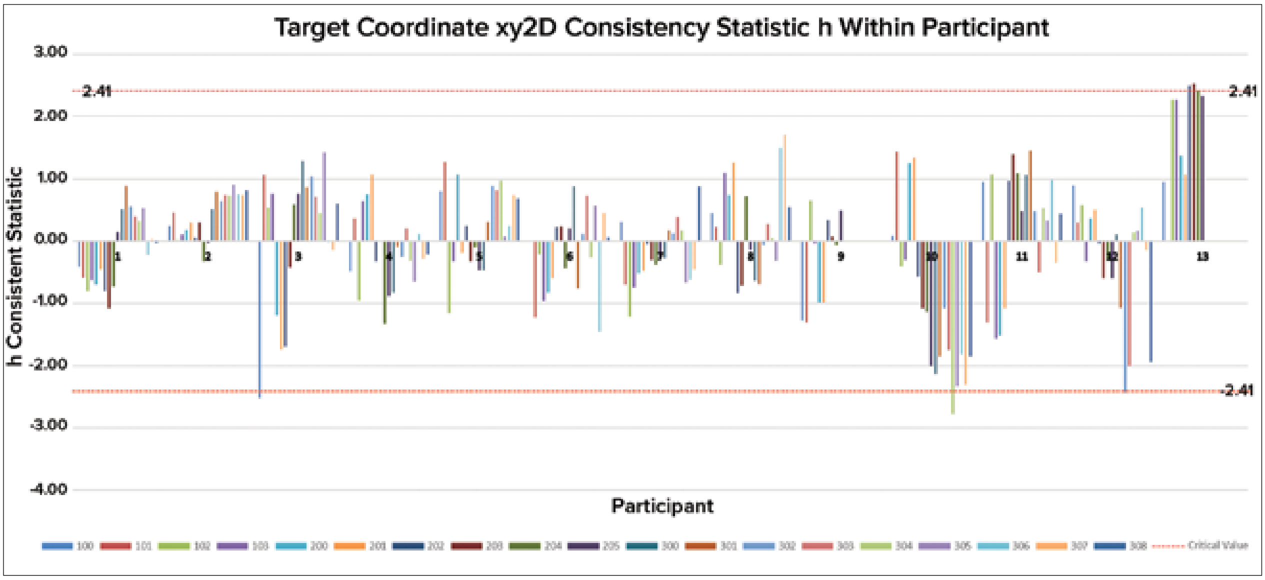


Fig. 6: Precision statistics: repeatability standard deviation and reproducibility standard deviation for 2-D (top) and 3-D (bottom) values (Note: 1 in. = 25.4 mm)



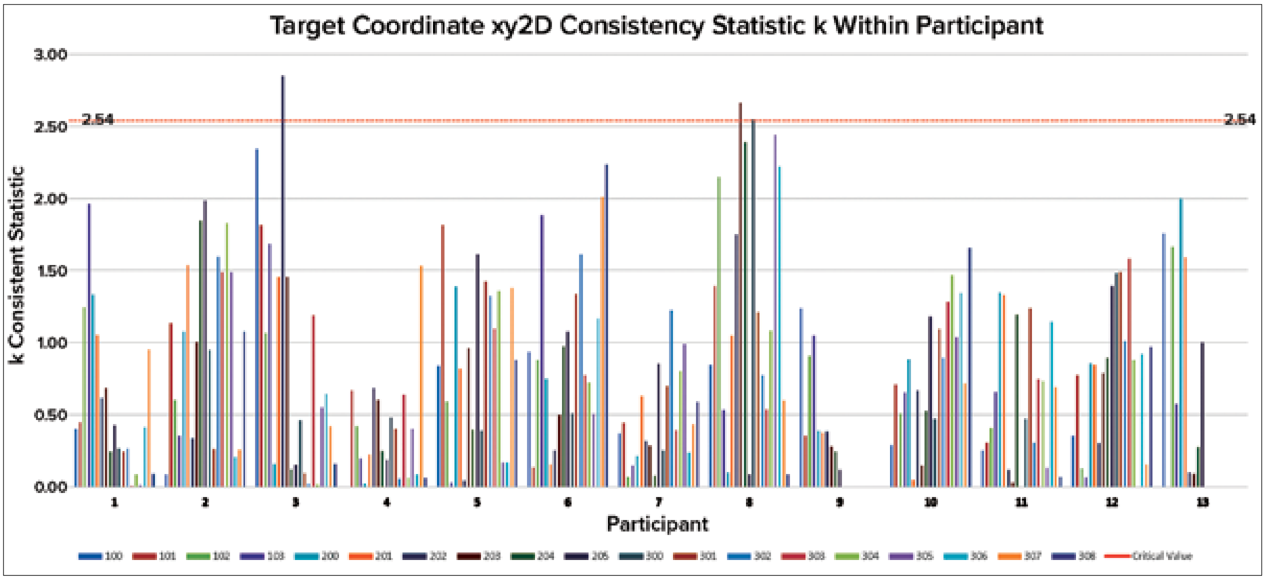
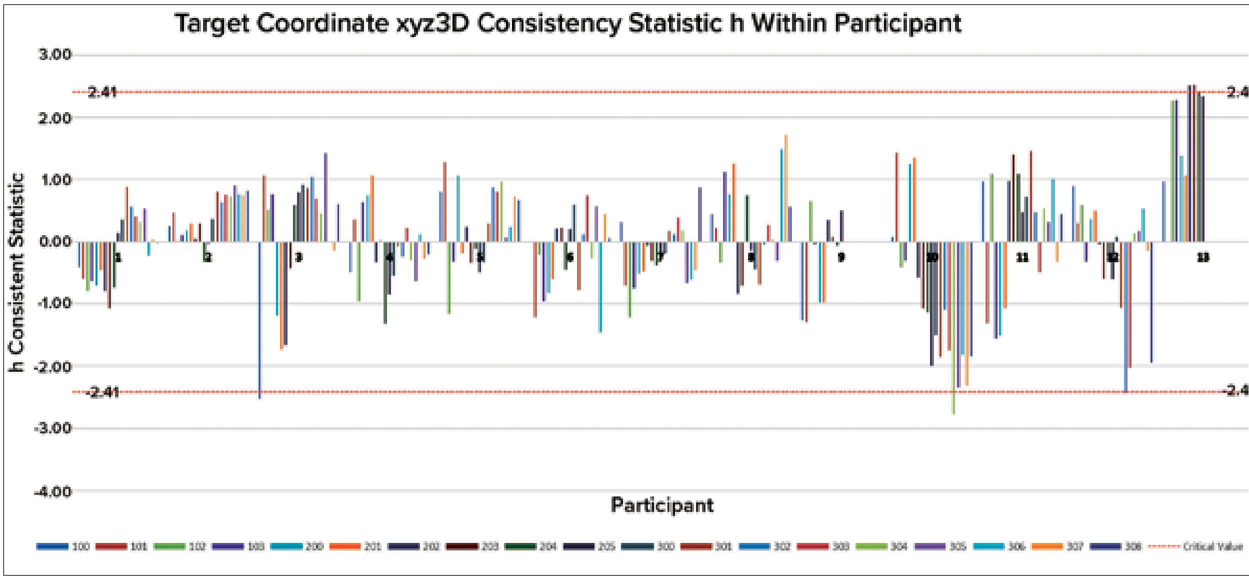


Fig. 7: Consistency statistics: *h*—the between-laboratory and *k*—the within-laboratory consistency of test results of participants

presented in Fig. 6. The data show that the standard deviation ranges from 0.020 to 0.060 in. (0.5 to 1.5 mm), with minimal variation between B/W targets on horizontal surfaces (100 series), B/W targets on vertical surfaces (200 series), and chalk-line intersections. Thus, the 95% repeatability and reproducibility limits, according to Eq. (12) and (13) in ASTM E691-23, range from 0.056 to 0.168 in. (1.4 to 4.3 mm), approximately 1/8 in. (3.2 mm).

Part 1b – Bias estimate

Two 1 second Leica total stations and one 0.5 second Trimble total station were used to establish reference ground truth measurements. Least squares adjustments were applied to all measurements at control points CP1 to 12, and the coordinates for all checkpoints were surveyed by four different parties, who reached a consensus on the final values. Root mean square error (RMSE) is a commonly used metric to assess the accuracy of a model or measurement system by calculating the square root of the average squared differences between predicted and observed values. It provides a measure of how well a model's predictions match actual observed data. A lower RMSE value indicates better accuracy, while a higher value suggests greater discrepancies between predicted and observed results. In this study, 456 target coordinates (x, y, and z) were entered into a spreadsheet as predicted values, and the corresponding errors were calculated using the target coordinates (x, y, and z) from total station measurements as observed values. The square root of the sum of squares was then computed to determine the 2-D error on the x-y plane and the 3-D error in space. Coefficients for the 95% confidence level (1.9600 for 1-D,



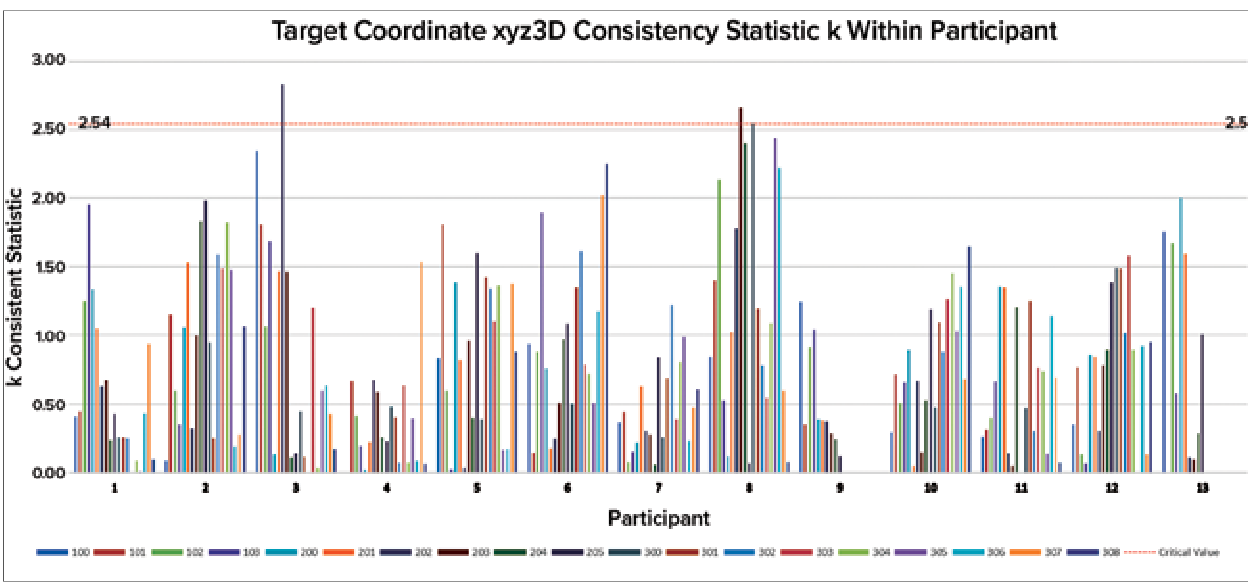


Fig. 7: Continued from previous page

1.7308 for 2-D, and 1.6166 for 3-D) were applied.[7] From the 456 data points, the 2-D RMSE at the 95% confidence level was calculated to be 0.125 in. (3.2 mm), and the 3-D RMSE at 95% was 0.142 in. (3.6 mm); refer to Table 2.

Part 1c – Comparison with 2018 study

The conclusion of the 2018 ASCC laser scan study highlighted that, due to the significantly smaller errors observed in the top three participants, using their standard deviations (SDs) as the standard uncertainty values would reduce the horizontal and vertical tolerances by approximately 50% and 30%, respectively. Table 3 indicates that the results of all 13 participants align with those of the top three participants from the 2018 study. Figure 8 presents histograms showing the error relative to ground truth values for 456 targets from all participants.

Part 2 – Tolerance interpretation from each participant with statistics

When it comes to as-built drawings showing deviations of existing concrete elements from their design locations—whether on the x-y plane or the z elevation—various drawing or report styles are used. These include spot as-builts indicating deviations from the design location in a 3-D model, 2-D CAD format or PDF drawing, slab elevation heat maps, vertical plumbness heat maps or section profiles, gridded elevation markups, scan-to-BIM models, 3-D deviation heat maps, and more. We know that processes such as averaging, resampling, smoothing, meshing, or best-fit techniques applied to point cloud data can introduce errors. One of the objectives of this study is to examine how these operations affect the end result when using a relatively precise and accurate point cloud data set.

Table 2:
Target errors from laser scan versus total station, in.

Bias statistics	Y	X	Z	XY (2D)	XYZ (3D)
Mean	−0.012	−0.002	−0.011	0.061	0.078
Range	0.377	0.354	0.397	0.251	0.323
Minimum	−0.203	−0.212	−0.184	0.002	0.008
Maximum	0.174	0.142	0.214	0.252	0.331
Count	456.000	456.000	456.000	456.000	456.000
RMSE	0.053	0.049	0.050	0.072	0.088
Confidence level (95.0%)	0.104	0.097	0.098	0.125	0.142

Note: 1 in. = 25.4 mm

Table 3:
Results of all 13 participants from the 2018 study

	2018 study, 8 participants			2018 study, 3 participants with lowest errors			2024 study, 13 participants		
	X	Y	Z	X	Y	Z	X	Y	Z
Count	310	310	310	114	114	114	456	456	456
Standard dev., in.	0.125	0.106	0.082	0.056	0.074	0.057	0.049	0.052	0.049
8 X U, in.	**1.002**	**0.852**	**0.653**	0.445	0.590	0.456	**0.395**	**0.413**	**0.393**
Min. tolerance	1 in. or > horizontal		5/8 in. vertical				1/2 in. or > horizontal and vertical		

Note: 1 in. = 25.4 mm

All participants were provided with a Revit model and a 2-D CAD file displaying the concrete elements to be examined. These digital design files share the same coordinate system as the survey controls provided, allowing the location and elevation deviations from the design to be inspected by overlaying the point cloud data with the digital design files. Participants were instructed to return deviation values from the design at four areas on the slab edge and slab openings (targets 100, 101, 102, and 103), as well as at two column surfaces (top and bottom) and walls (top and bottom). To ensure consistency in comparison, targets from the 100 and 200 series can be used to evaluate deviations at the same spots. Alternatively, the actual edges of the slabs can be used, as the targets near the edges were established with an exact 6 in. offset. Similarly, the column concrete surfaces can be used, as the targets were directly attached to the concrete surfaces.

Ground truth was established by importing total station measurements of these targets into an Autodesk Civil3D floor plan. Perpendicular measurements were taken from the total station points to the concrete elements to determine the deviation values on the x-y plane for all 10 targets (or concrete elements). Similarly, deviations in the z-axis for the four slab targets were calculated by subtracting the design elevations from the total station elevation measurements at these four targets. The deviation values were analyzed using their absolute values.

Eight participants were able to provide deviation values, resulting in 80 data points for the x-y plane and 32 data points for the z-axis used in the analysis. Table 4 presents the statistics and comparison of the 10 target (concrete element) deviation values from the 19 target coordinates measured directly from the laser scan. The standard deviations of the XY and Z deviations were approximately double those of the direct laser scan measurements, indicating that errors were introduced when participants analyzed the deviations from the design. One contributing factor identified was that one target was located in a depressed area of the slab, meaning the design slab elevation did not align with the "flat" area, which some participants failed to account for, resulting in human error. Figure 9 provides an example illustrating how point cloud noise, the best-fit algorithm, or human error can affect the end result when determining tolerance compliance. The deviation measurements, ranging from 0.017 to 0.030 in. (0.43 to 0.76 mm), were observed from the best plane extraction (blue plane), point cloud on the edge, and two meshing parameters. This example covers a small area, but the impact could be more significant at a larger scale.

Conclusion and Recommendations

The 2018 ASCC laser scan study suggested that it would be appropriate to use a laser scanner for specification compliance when measuring a vertical tolerance of 5/8 in. or more and a horizontal tolerance of 1 in. or more. It was also found that the top three participants with the lowest errors

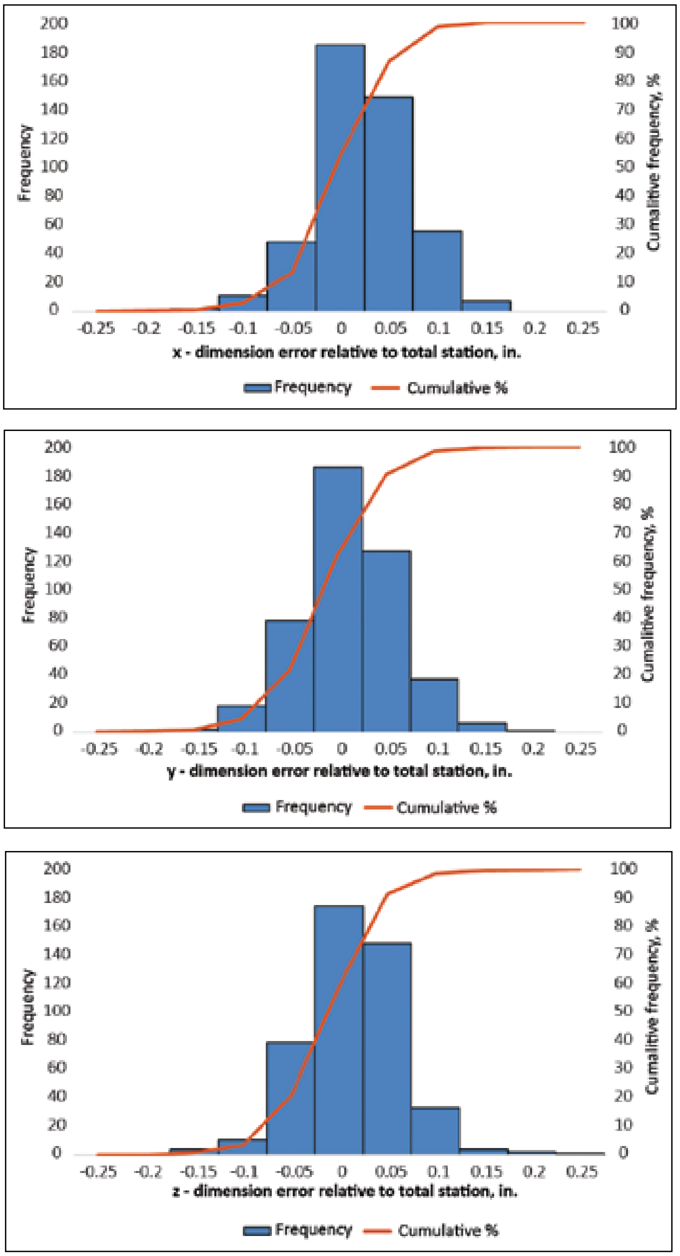


Fig. 8: Histograms showing the error relative to ground truth values for 456 targets from all participants (Note: 1 in. = 25.4 mm)

were able to reduce the horizontal and vertical tolerance by approximately 50% and 30%, respectively, by using SDs as the standard uncertainty values. A concept of uncertainty ratio was introduced to determine how much measurement tolerance should be allocated for construction accuracy. ANSI/NCSL Z540.3:2006[8] test uncertainty ratio (TUR) 1:4 was introduced and applied in that study.

In summary, it was suggested that the ratio between the standard deviation of the mean (or individual measurements) and the construction tolerance should be 1:8.

The U.S. Institute of Building Documentation (USIBD) Level of Accuracy (LOA) Specification Guide[9] provides heuristic guidance for sensor measurement standard deviation in regard to overall tolerance. Generally, the SD has to be roughly one-fifth of the overall tolerance for P = 30% and 1-a = 95% to match the manufacturing requirements, where P represents the proportion of measurement tolerance in regard to overall tolerance.[8]

ACI PRC-117.114, "Guide for Tolerance Compatibility in Concrete Construction,"[10] provides an example in Section 3.4.4. It is reasonable to have a measurement precision at 99.7% confidence level (three standard deviations) to be one-third of the construction tolerance.

Based on similar studies and recommendations from various industries, as well as the analysis from this study, the authors repeated the 8x measurable SD to the applicable concrete construction tolerance in the conclusions. It is reasonable to recommend the use of a TLS for specification compliance when measuring horizontal and/or vertical tolerances of 0.5 in. (13 mm) or more.

Recognizing the growing importance of laser scanning in construction, ACI Subcommittee 117-L, Laser Scanning, has focused its efforts on concrete verification using TLS for this study. This emphasis stems from the unique advantages TLS offers over other methods for this purpose. First, TLS provides highly accurate and dense 3-D data capture, enabling precise measurements of concrete surfaces. This level of detail is crucial for identifying subtle deviations from design specifications and ensuring compliance with tolerances. Secondly, TLS offers a noncontact measurement approach, minimizing the risk of damaging or disturbing the concrete

Table 4:
Comparison of 10 target (concrete element) deviation values from 19 target coordinates measured directly from the laser scan

19 target coordinates			Deviation from scan to design on 10 targets	
Statistic	X and Y target analysis	Z target analysis	X and Y deviation from design	Z deviation from design
Count	456	456	80	32
Minimum, in.	0.002	−0.184	0.000	0.000
Maximum, in.	0.252	0.214	0.263	0.431
Average, in.	0.061	−0.011	0.068	−0.011
SD, in.	0.038	0.049	0.065	0.112

Note: 1 in. = 25.4 mm

surface during inspection. This is particularly important for freshly placed concrete or delicate finishes. Finally, TLS enables efficient data collection, reducing the time and labor required for comprehensive inspections compared to traditional methods.

So, what is next? While the adoption of laser scanning and reality capture technologies in the concrete industry enhances project efficiency, reduces costs, and improves quality and safety, it is important to acknowledge the potential dependency on such technologies. Overreliance on equipment and software that may become outdated or prone to technical issues could pose challenges. Many organizations, including but not limited to ACI Subcommittee 117-L, The COMMITTEE (a new testing organization), the Reality Capture Network (RCN), and the U.S. Institute of Building Documentation (USIBD), have taken steps to test these technologies. Therefore, the authors encourage further studies to evaluate these technologies on active construction projects to better understand their long-term viability and limitations in real-world applications.

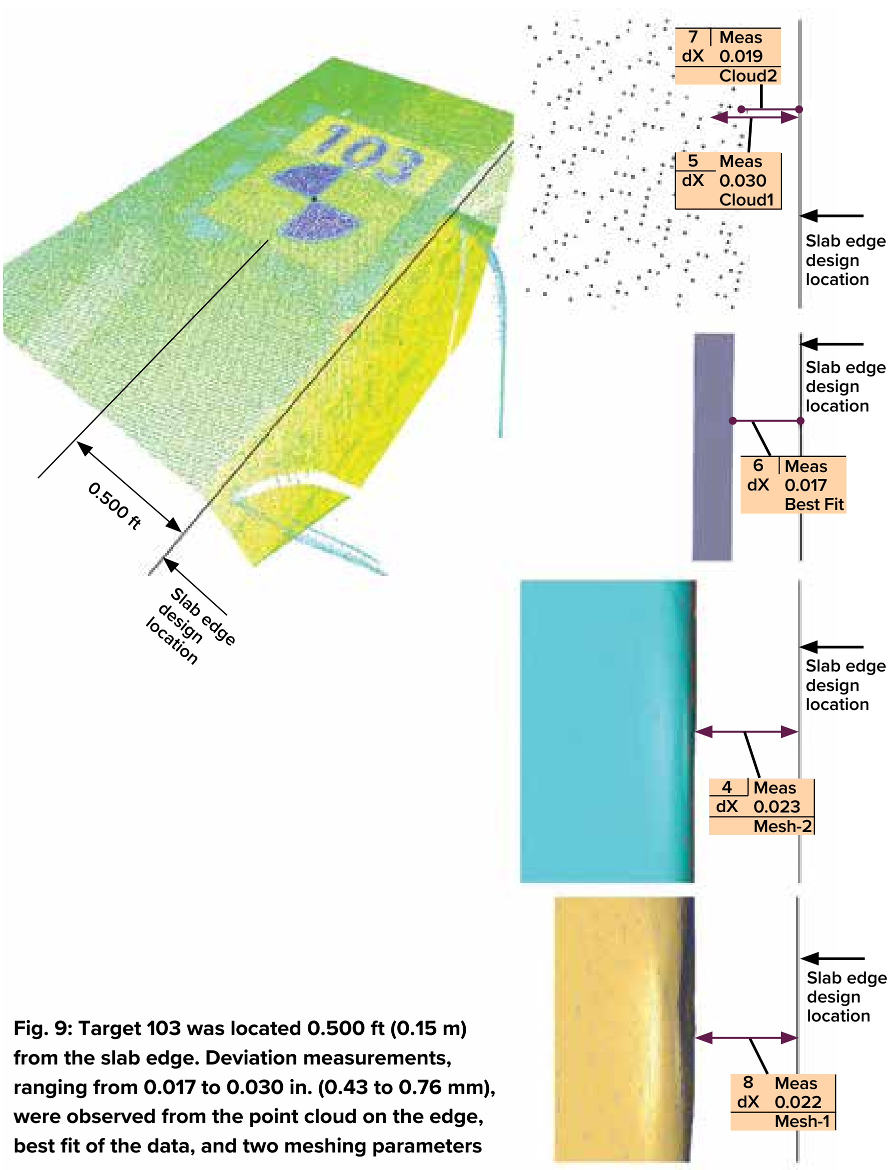


Fig. 9: Target 103 was located 0.500 ft (0.15 m) from the slab edge. Deviation measurements, ranging from 0.017 to 0.030 in. (0.43 to 0.76 mm), were observed from the point cloud on the edge, best fit of the data, and two meshing parameters

Project Credits

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Selected for reader interest by the editors.

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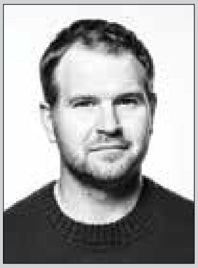

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