ASCC 3-D Laser Scanning Study

Part 1: Eight participants used scanners to determine target coordinates

by William Paul, James Klinger, and Bruce A. Suprenant

Joint ACI-ASCC Committee 117, Tolerances, is preparing a new document, "Guide to the Use of 3-D Laser Scanning for Concrete Tolerances." In anticipation of that document, the American Society of Concrete Contractors (ASCC) organized a study to evaluate laser scanning for concrete tolerance applications. The study was conducted on a construction site in Walnut Creek, CA, on October 6 and 7, 2018 (Fig. 1). Eight participants (each comprising one to three individuals) scanned portions of the project, and their measurements were compared against independently obtained reference data.

Study Objectives

Our study was developed to evaluate the measurement system variation for laser scanning equipment used on construction projects. While this technology has become an increasingly popular tool for quality assurance and quality control on construction sites, there have been few evaluations of laser scanner measurement system variation. With the goal of developing resource data for the upcoming ACI Committee 117 guide, three main quantities were evaluated on a construction site:

- Accuracy of target coordinates;
- Accuracy of floor flatness and levelness values (F-numbers per ASTM E1155, "Standard Test Method for Determining F_F Floor Flatness and F_L Floor Levelness Numbers") calculated using scanner output; and
- Repeatability and reproducibility of F-numbers.

A separate article will discuss the F-number data.

Fig. 1: The project site comprised a ground-level slab (lower left) and a podium level (right) *(photo courtesy of BKF Engineers)*

Structure Information

The construction project that served as the evaluation site is a hybrid concrete "podium" and wood-framed apartment structure commonly found in California, featuring a basement parking level approximately 10 ft (3.0 m) below grade, a mixed commercial/residential level (ground level), and an elevated residential level approximately 12 ft (3.7 m) above the ground floor (podium level). The podium level was designed to support five floors of wood-framed residential units. The ground and podium levels are post-tensioned elevated slabs supported by cast-in-place columns and shotcrete walls. Test areas at each level were about 6000 ft^2 (about 560 m^2).

The ground-level test area consists of a nominal 8 in. (203 mm) thick post-tensioned slab with a hard-trowel finish and a limited number of penetrations and conduit stub-ups. The slab was placed on August 28, 2018; the tendons were stressed on August 31, 2018; and the formwork was stripped and the slab reshored on September 3, 2018. At the time of the test, the top surface of the slab had been broom-cleaned. Also, the columns and shotcrete walls for support of the podium level were already in place.

The podium-level test area consists of a nominal 13 in. (330 mm) thick post-tensioned slab with a hard-trowel finish. The test area was part of an overall placement area of 17,000 ft^2 (1580 m^2) placed on October 5, 2018. The post-tensioning tendons had not been stressed at the time of the test.

Fig. 2: The podium-level slab included many protruding anchor rods *(aerial photo courtesy of BKF Engineers)*

Because the podium slab is the foundation for the wood-framed structure above, it includes many protruding anchor rods for the framed structure's shear walls and sill plates. As can be expected in residential construction, the slab also contains many sleeves, conduit stub-ups, and similar discontinuities (Fig. 2).

Measurements

Target coordinates

For this portion of the study, the participants used scanner data to define the coordinates of targets that had been previously affixed to horizontal and vertical surfaces. Determined values were then compared against coordinates found independently by a surveyor using a total station.

Regardless of the application, laser scanners provide a point cloud—the coordinates of millions of points on the surfaces within the sight line of the instrument. The point coordinates can be used to determine the surface elevation of slabs, locations of walls and columns, or other dimensional data. The study participants were asked to provide the point coordinates of 10 targets. To evaluate repeatability and reproducibility, the participants were directed to perform a laser scan two times at each of two locations. Each participant was provided with a data form to enter their results.

Fourteen targets were placed on both the ground- and podium-level slabs. All targets on the podium level were placed on the concrete slab surface. On the ground level, 10 targets were placed on concrete walls (Fig. 3) and columns and four targets were placed on the slab surface. The targets were located such that multiple laser setups would have to be used to obtain a line of sight. This was done to ensure that the participants had to stitch together (register) the individual scans in three dimensions to create a larger, contiguous point cloud. For analysis, all 14 targets were surveyed with a total station from three separate locations to provide the "reference" coordinates. Coordinates for four targets on each level were provided to the participants for control points.

Participant information

The participants included personnel from four contractors, two consultants, and representatives from two laser equipment manufacturers. While many of the participants were local to the San Francisco-Oakland Bay area, there were also participants from Colorado, Texas, and Florida. All volunteered. Further,

Fig. 3: Ten targets were placed at various locations on vertical surfaces (concrete walls and columns at the ground level) for participants to determine their point coordinates. The reference target point coordinates were obtained using a total station at three locations. Ten targets were also placed at various locations on the horizontal concrete surface at the podium level *(aerial photo courtesy of BKF Engineers)*

Table 1:
Laser scanner type and experience level for participants

Participant	Laser scanner type	Experience level (number of previous scans)
A	Faro S150	10 to 100
B	Leica P40	100 to 250
C	Leica RTC360	More than 250
D	Faro S150	More than 250
E	Faro X330	More than 250
F	Faro S350	More than 250
G	Trimble TX8	More than 250
H	Leica P40	More than 250

Note: Faro, Leica, and Trimble indicate scanners marketed by Faro Technologies, Inc., Leica Geosystems AG, and Trimble, Inc., respectively

they and their companies were not reimbursed for their time or travel costs.

Each participant worked independently. All were instructed to use what they considered to be best practices for the work. Data reporting forms were provided, but the participants did not share data with each other. Raw data was shared with the participants after all had completed measurements; however, participants are identified anonymously in the dataset. Information on each participant's laser type and experience level are shown in Table 1.

Target Coordinates—Basic Data
Reference target coordinates

A Leica total station was used to survey all the target coordinates from three locations. With this total station, the measured accuracy for the target coordinates at a 95% confidence level was 0.024 in. (0.6 mm). This data was used as the "reference" or "control" data for comparison with the measurements taken by the participants using laser scanners. This approach was chosen based on a recommendation "that ideally laser scanner measurements should be compared to measurements by a total station to determine accuracy."[1] Other investigators[2] have also used a total station to compare with laser scanning measurements, and one investigator[3] located reference points measured from four locations with a total station.

Participant target coordinates

The reference x-, y-, and z-coordinates were entered into a spreadsheet, along with each participant's measured x-, y-, and z-coordinates. Measurements were recorded in units of feet, to at least four decimals. The participants' coordinate measurements were subtracted from the reference coordinates to determine the error values (in units of ft), and these were then converted to units of inches. Finally, the error in x and y was calculated using the square root of the sum of the squares (SRSS) of the x-error and y-error. The error in z required no further calculation. Tables 2 and 3 summarize the error analyses for the ground- and podium-level slab measurements for each participant. For each day of the study, the participant's minimum, average, maximum, and standard deviation (SD) of the error in x and y and the error in z are tabulated.

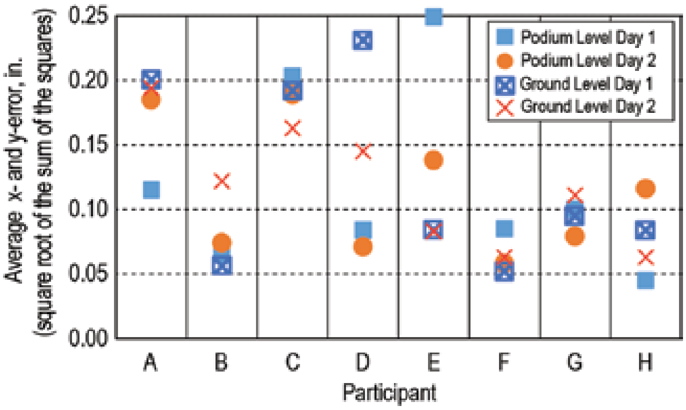


Fig. 4: The average SRSS x-y error for each laser participant varied as shown. Participants B, F, G, and H had SRSS x-y errors less than 0.15 in. (4 mm) and good repeatability of the four scans (Note: 1 in. = 25 mm)

Target coordinate error observations

Figure 4 shows the average SRSS errors (calculated using x- and y-coordinates) for the 10 targets on both the podium and ground levels for each of the two scans (Days 1 and 2). For all four scans, SRSS error ranges found for Participants C, F, and G were under about 0.05 in. (1.3 mm), while SRSS error ranges found for Participants A, B, and H were under 0.10 in. (2.5 mm). The largest SRSS error ranges were for Participants D and E, with values of about 0.20 in. (5 mm). An SRSS error of 0.20 in. would be an error of 0.14 in. (3.5 mm) in both the x and y directions. Figure 4 also shows that the repeatability of laser scans was very good for most participants. However, the SRSS error range between repeated measurements for Participants D and E was about 0.15 in. (3.5 mm).

As noted previously, the 10 targets at ground level were placed on vertical elements and the 10 targets on the podium level were all placed on the horizontal concrete surface. The SRSS errors and SD values for each level were essentially the same, with average SRSS errors of 0.121 in. (3.1 mm) on the ground level and 0.116 in. (2.9 mm) on the podium level. The corresponding SD values were 0.068 in. (1.7 mm) on the ground level and 0.087 in. (2.2 mm) on the podium level.

The maximum error can be found in Tables 2 and 3. Participants B, F, G, and H had maximum SRSS errors of less than 0.30 in. (7.5 mm); Participant C had a maximum SRSS error of less than 0.50 in. (12.5 mm); Participant A had a maximum error of 0.75 in. (19 mm); and Participant D had an error that exceeded 1 in. (25 mm).

Figure 5 shows the average z-error for the 10 targets on the ground and podium levels. The average z-error was very consistent at 0.06 in. (1.5 mm) or below, except for Participant A. Although the maximum z-error for Participant A was 0.20 in., it appears that the high error is an outlier—the other three z-errors found for Participant A were all less than

Table 2:
Ground-level error analysis for target coordinates

Participant	Day	Error in x and y (SRSS of [reference – measured] for x and y), in.				Error in z (reference – measured), in.			
		Minimum	Average	Maximum	Standard deviation	Minimum	Average	Maximum	Standard deviation
A	1	0.147	0.200	0.270	0.051	−0.091	0.004	0.080	0.064
	2	0.147	0.194	0.270	0.045	−0.091	0.004	0.080	0.064
B	1	0.020	0.056	0.137	0.037	0.020	0.056	0.137	0.037
	2	0.050	0.122	0.218	0.054	−0.051	0.044	0.163	0.066
C	1	0.036	0.192	0.323	0.092	−0.095	−0.001	0.138	0.079
	2	0.028	0.163	0.242	0.069	−0.094	0.002	0.126	0.069
D	1	0.010	0.231	1.097	0.348	−0.084	0.063	0.340	0.112
	2	0.076	0.145	0.240	0.063	−0.052	0.042	0.187	0.078
E	1	0.040	0.084	0.149	0.036	−0.087	0.012	0.203	0.085
	2	0.037	0.083	0.168	0.042	−0.097	−0.010	0.131	0.077
F	1	0.020	0.052	0.078	0.020	−0.097	0.021	0.164	0.087
	2	0.028	0.063	0.115	0.030	−0.025	0.025	0.110	0.051
G	1	0.027	0.095	0.223	0.055	−0.450	−0.062	0.218	0.199
	2	0.035	0.111	0.172	0.043	−0.330	−0.062	0.278	0.180
H	1	0.007	0.084	0.233	0.069	−0.090	0.010	0.107	0.067
	2	0.020	0.063	0.121	0.031	−0.090	−0.015	0.089	0.059

Note: All targets on vertical surfaces (concrete columns and walls); 1 in. = 25 mm

Table 3:
Podium-level error analysis for target coordinates

Participant	Day	Error in x and y (SRSS of [reference – measured] for x and y), in.				Error in z (reference – measured), in.			
		Minimum	Average	Maximum	Standard deviation	Minimum	Average	Maximum	Standard deviation
A	1	0.025	0.115	0.280	0.087	−0.027	0.010	0.056	0.030
	2	0.051	0.185	0.758	0.214	0.060	0.203	0.401	0.127
B	1	0.019	0.065	0.116	0.036	−0.048	0.005	0.048	0.030
	2	0.000	0.074	0.157	0.045	−0.088	−0.039	0.012	0.039
C	1	0.060	0.203	0.401	0.127	−0.072	0.026	0.096	0.057
	2	0.000	0.189	0.420	0.124	−0.048	0.005	0.048	0.030
D[*]	1	0.000	0.084	0.246	0.098	−0.004	0.034	0.068	0.024
	2	0.013	0.071	0.284	0.078	−0.079	0.003	0.058	0.048
E	1	0.069	0.249	0.578	0.180	−0.004	0.057	0.095	0.031
	2	0.007	0.138	0.245	0.086	−0.023	0.036	0.100	0.043
F	1	0.016	0.085	0.150	0.038	−0.061	−0.007	0.042	0.032
	2	0.009	0.058	0.116	0.032	−0.004	0.057	0.095	0.031
G[†]	1	0.016	0.100	0.217	0.076	−0.072	−0.012	0.120	0.057
	2	0.037	0.079	0.146	0.034	−0.072	−0.012	0.120	0.057
H[‡]	1	0.000	0.045	0.124	0.041	−0.048	0.029	0.096	0.062
	2	0.000	0.116	0.251	0.096	−0.048	0.029	0.096	0.062

[*] Participant D measured coordinates for five targets on Day 1

[†] Participant G provided two data points that were not included in this analysis because they were off by more than 20 ft (6 m). This outlier data was assumed to have resulted from an input typo

[‡] Participant H measured seven target coordinates on both days

Note: All targets on horizontal surfaces (concrete slab). Unless noted otherwise, participants measured values for all 10 targets; 1 in. = 25 mm

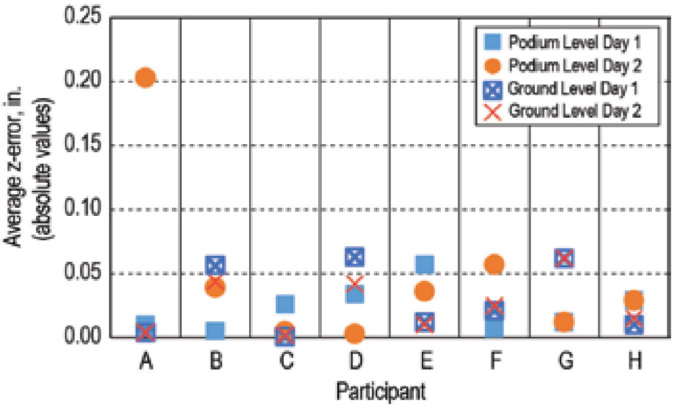


Fig. 5: Except for laser participant A, the z-errors were below 0.06 in (1.5 mm) and showed good repeatability for both the ground and podium levels (Note: 1 in. = 25 mm)

0.02 in. (0.5 mm). The repeatability between measurements was also very good except for Participant A.

The average z-errors were 0.008 in. (0.2 mm) on the ground level and 0.027 in. (0.7 mm) on the podium level, and the average SDs were 0.086 in. (2.2 mm) on the ground level and 0.048 in. (1.2 mm) on the podium level.

Target Coordinates—Validity of Data

Prior to using target coordinate data to recommend tolerances, the data is first compared to the results obtained by other investigators to establish its validity.

Vertical accuracy

Root Mean Square Error (RMSE) is a widely used statistic for a geographic information system (GIS). RMSE is a measure of the error between two datasets, and it can be used to compare a predicted value and an observed value. The National Standard for Spatial Data Accuracy[4] (NSSDA) defines vertical accuracy at the 95% confidence level of RMSE. In the ASCC study reported herein, the RMSE can be calculated using the elevation points determined using laser scanners (predicted value) compared to the total station surveyed elevation points (observed value).

Hiremagalur et al.[1] reported that the Caltrans vertical accuracy requirement for hard surfaces is 0.28 in. (7 mm). They set up an investigation using survey data of Old Hutchison Drive, collected by Caltrans using conventional means (a total station for x-y [Easting-Northing], and leveling instruments for z [elevation]) compared to data from various laser scanners. Measurements were made on five points for each cross section of the roadway at intervals of 5 m (16 ft) along the roadway pavement, out to a maximum range of 120 m (394 ft) in both directions from the scanner. The investigators reported the 95% RMSE from data obtained from two separate measurements using Leica scanners, a Trimble scanner, and an Optech scanner were 0.28 in., 0.42 in. (10.7 mm), and 0.47 in. (12.0 mm), respectively.

For the ASCC study, the laser scanner and total station elevation points were compared at 10 points on the ground level by eight different investigators, twice. A total of 160 data points were analyzed. The 95% RMSE from this data is 0.20 in. The same analysis was conducted for the 160 data points on the podium level, resulting in a 95% RMSE of 0.12 in. (3 mm). This compares very well with the 95% RSME results from Leica, Trimble, and Optech scanners used in the Caltrans study reported by Hiremagalur et al.[1] In fact, the vertical accuracy exhibited in the ASCC study is very good.

Jaselskis et al.[5] performed pilot studies on laser scanning for the Iowa Department of Transportation using a Cyrax laser scanner. They measured the roadway centerline, lane edge, and shoulder elevations for a section of I-235. The difference in elevation measurements obtained using the scanner point cloud data and using traditional surveying equipment ranged from 0.04 to 0.35 in. (1 to 9 mm). For the ASCC study, 160 elevation point measurements were obtained for the ground-level slab. The difference between the vertical elevations obtained using the total station and the laser scanner ranged from 0.08 to 0.34 in. (2 to 9 mm). For the 160 elevation point measurements on the podium level, the difference between vertical elevations obtained using the total station and the laser scanner ranged from 0.03 to 0.18 in. (0.7 to 4.6 mm).

Horizontal accuracy

We found no other published investigator results that could be compared directly to the results obtained for x-y point coordinates in the ASCC study. A few investigators reported the errors in range or distance measurements (which would involve measurement of two points, rather than measurement of a single point relative to a fixed coordinate).[6] NIST[2] developed two methods (line-plane intersection and geometric center) of measuring distance accuracy that were scanned at various ranges up to 500 ft (150 m). For this study, the repeated measurements at the ground-level and podium-level targets resulted in 310 measurements. The average x- and y-error of the total measurements for this study was 0.12 in., with SD of 0.06 in. If two points had the same error parameters, then the average distance error would be 0.24 in. (6 mm), and the SD would be 0.08 in. (2 mm). The average distance error versus range distance results from Reference 2 are shown in Fig. 6. Similar to vertical accuracy, the x-y measurements in this study provide accuracy comparable to other studies.

Setting Tolerance Limits for Laser Scanning

A tolerance consists of two parts: one accounts for measuring and the other for construction (refer to the Appendix). As an example, the total station used for surveying the targets had an accuracy of 0.002 ft (0.0006 m) at the 95% level. If we multiply the 0.002 ft by 4 and convert to inches, the smallest tolerance that we should measure with a total station is 0.096 in. (2.4 mm). In other words, the instrument is appropriate for measurement of tolerances that are greater than 1/8 in. (3.2 mm).

For laser scanning, Fig. 7 illustrates the errors determined in this study. Tables 4, 5, and 6 provide the target error

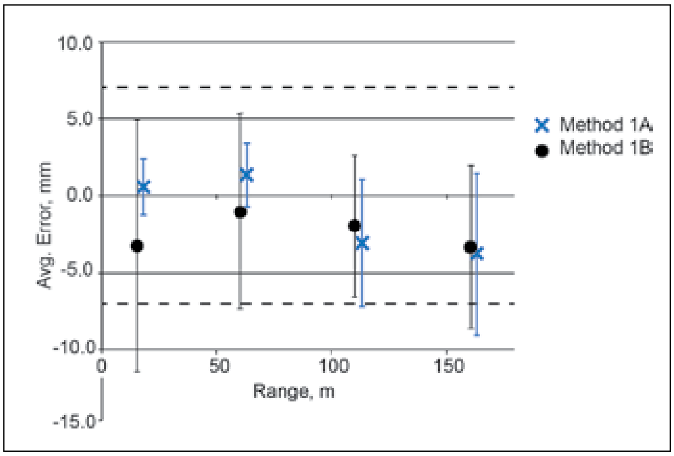


Fig. 6: Error versus range (based on Ref. 2, Fig. 21). Points represent the averages for a given range over all reflectivities, angles of incidence, and azimuths. There were no data for the 2% reflective target for ranges greater than 60 m (197 ft). The error bars are the SDs of the data (Note: Range values for the two data sets have equal values but are plotted with a slight offset for clarity; 1 mm = 0.04 in.; 1 m = 3.3 ft)

analysis based on the data for the ground and podium levels and on all 310 individual target measurements. Based on the data in this study, our analyses indicate 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. or more.

Best Practices—The Future

The upcoming ACI-ASCC Guide for 3-D laser scanning will need to focus on best practices that would lower the scanning error. The participants in this study were allowed

Table 4:
Vertical target error analysis

	Ground	Podium	Total
Count	160	150	310
Minimum	−0.450	−0.336	−0.450
Maximum	0.340	0.180	0.340
Average	0.013	0.012	0.0128
SD	0.097	0.060	0.0816
8 × U	0.779	0.484	0.653

Table 5:
X target error analysis

	Ground	Podium	Total
Count	160	150	310
Minimum	−0.561	−0.673	−0.673
Maximum	1.083	0.446	1.083
Average	0.008	0.010	0.009
SD	0.128	0.123	0.125
8 × U	1.025	0.980	1.002

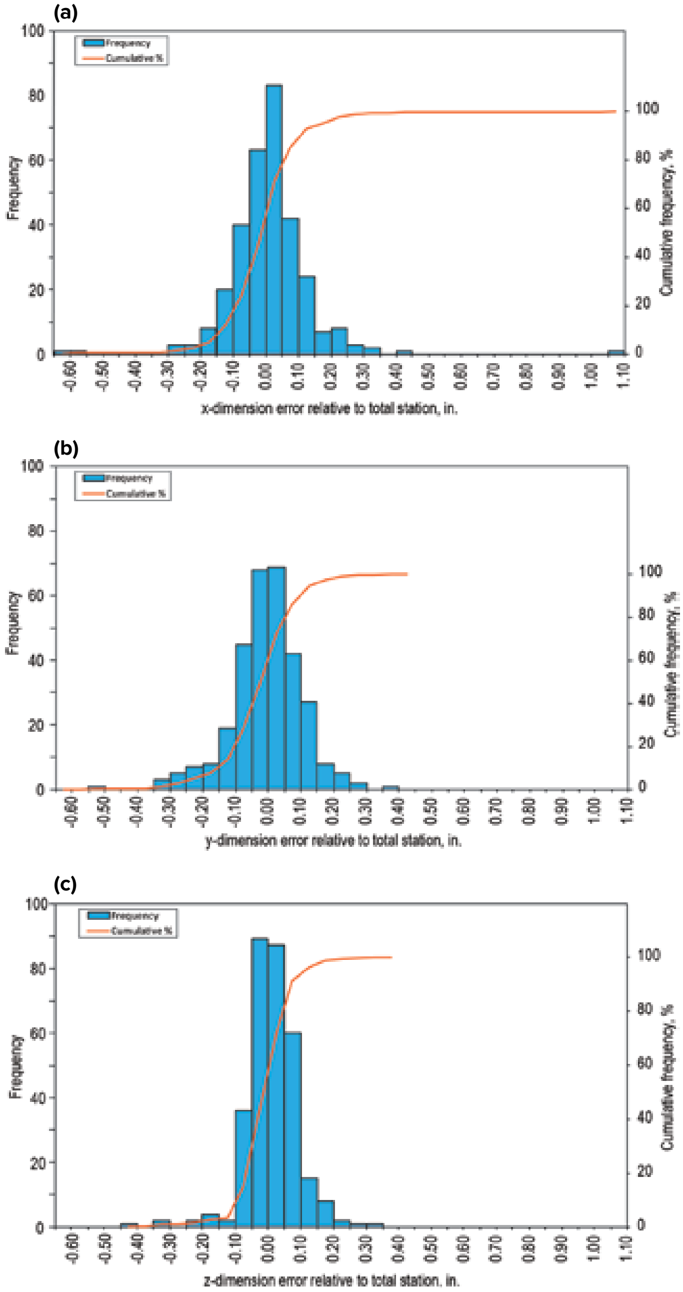


Fig. 7: Histograms showing the error relative to measurements taken using a total station for 310 points measured by participants using laser scanners: (a) error in x-dimension; (b) error in y-dimension; and (c) error in z (vertical) direction

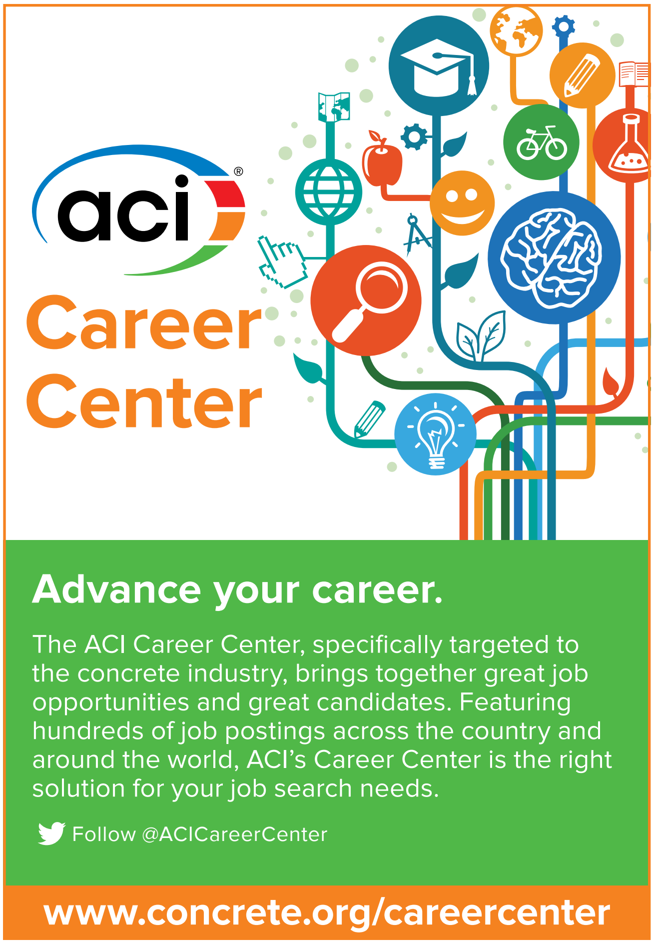
Table 6:
Y target error analysis

	Ground	Podium	Total
Count	160	150	310
Minimum	−0.295	−0.516	−0.516
Maximum	0.280	0.360	0.360
Average	−0.007	−0.004	−0.005
SD	0.101	0.112	0.106
8 × U	0.810	0.897	0.852

Table 7:
Comparison of errors for eight participants versus three participants with lowest errors

	Eight participants			Three participants with lowest errors		
	X	Y	Z	X	Y	Z
Count	310	310	310	114	114	114
Minimum	−0.673	−0.516	−0.450	−0.157	−0.232	−0.097
Maximum	1.083	0.360	0.340	0.121	0.212	0.164
Average	0.009	−0.005	0.013	−0.004	−0.011	0.013
SD	0.125	0.106	0.082	0.056	0.074	0.057
8 × U	1.002	0.852	0.653	0.445	0.590	0.456

to choose their own methods in real-world conditions at an active construction site to obtain an end result. Providing guidance for best practices should lower the error, allowing for smaller tolerances to be measured by laser scanning for specification compliance. As an example, we separated out the three participants with the lowest errors and compared them to all eight participants in Table 7. Because the errors are much smaller for these three participants, using their SDs as the standard uncertainty values would lower the horizontal and vertical tolerances by about 50 and 30%, respectively. These three participants will be discussing their best practices at the ASCC Laser Scanning Workshop in Las Vegas, NV, on January 21, 2019.



Project credits

Tony Joyce, Avalon Bay Communities, Owner/GC; Tom Sprague, Don Thornburg, and Marty Conroy, Conco, Concrete Contractor; Jose Jacobo, Hector Campos-Diaz, and Anil Nethisinghe, Consolidated Engineering Laboratories (CEL), Testing Agency; and Eric Peterson, Webcor Construction LP, Observation.

Laser scanning participants:

- Andy Huntley, TAS Commercial Concrete;
- Aniruddha Anjana, Baker Concrete Construction;
- Cutter Shea, Faro Technologies, Inc.;
- Leo Castillo and Leeroy Duarte, VEC, INC.;
- Nathan Culver and Gustav Choto, Trimble Inc.;
- Kevin Stein, Steve Smith, and Heather White, BKF Engineers;
- Josh Engelbrecht, DPR Construction;
- Brandon Kovarick, CECO Concrete Construction; and
- Leo Zhang, Conco.

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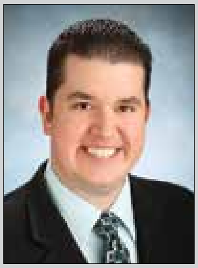

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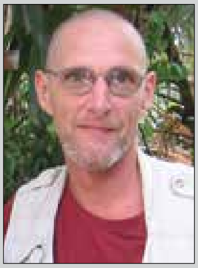

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Appendix

Parts of a Tolerance

ACI 117-10[*] defines a tolerance as the permitted deviation from a specified value. To determine if an as-built concrete structure meets the specified deviation, a measurement must be made. Thus, the accuracy of the measuring device is a part of the overall tolerance, as the overall tolerance includes both a measurement part and a construction part (as shown in the figure).

Two questions should be answered to determine the tolerance: First, what should be used as the measurement accuracy? Second, how large or small should the measurement accuracy be as part of the total tolerance? In other words, how much tolerance should be allocated for construction accuracy?

ANSI/NCSL Z540.3-2006[†] provides requirements for answering the first question through its definition of the test uncertainty ratio (TUR). TUR is defined as: "the ratio of the span of the tolerance of a measurement quantity subject to calibration, to twice the 95% expanded uncertainty of the measurement process used for calibration." Setting the expanded uncertainty at the 95% confidence level essentially doubles the standard uncertainty value. The definition of the TUR further calls for "twice the 95% expanded uncertainty," effectively placing the endpoints of the tolerance span on each side of the mean. In the ACI 117 specification, this is considered using a ± tolerance. Lastly, the ANSI/NCSL Z540.3-2006 requires that the TUR be set at 4:1 if it is not practical to estimate the probability that incorrect acceptance decisions will result from calibration tests—that is the case for laser scanning tools.

It is also necessary to determine if the standard uncertainty is the SD of the mean or the SD of individual measurements. That choice depends on how the tolerance is determined. In the ACI 117 specification, individual measurements, not averaged measurements, are compared to the specified tolerance. Thus, we recommend that the standard uncertainty is the sample SD representing the individual measurements. Of course, this will be larger than the SD of a mean. ACI Committee 117 is currently drafting "Specifications for Tolerances for Concrete Construction and Materials," and this document is expected to use a similar definition for tolerance.

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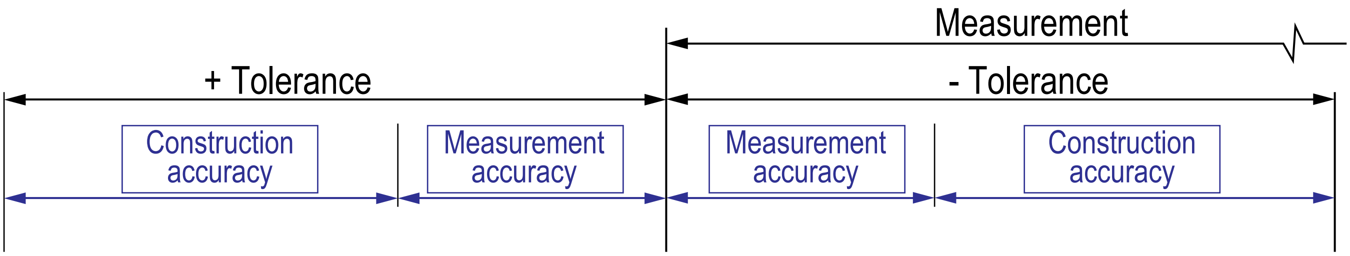
[*] ACI Committee 117, "Specification for Tolerances for Concrete Construction and Materials (ACI 117-10) and Commentary (Reapproved 2015)," American Concrete Institute, Farmington Hills, MI, 2010, 76 pp.

[†] "ANSI/NCSL Z540.3-2006—Requirements for the Calibration of Measuring and Test Equipment," 6th edition, NCSL International, Boulder, CO, 2013, 11 pp.



A specified tolerance includes a measurement accuracy and a construction accuracy