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Abstract

The recently revised ASME B89.4.19-2021 and ISO 10360-10:2021 standards for laser trackers include a new interim test that is comprehensive and more sensitive to systematic errors than the interim tests in the previous versions of the standards, i.e., the ASME B89.4.19-2006 and ISO 10360-10:2016. This interim test can be performed by users periodically in the field to assess the health of their trackers. There are two components to this interim test – the first is designed to detect geometric errors in laser trackers while the second is designed to assess the performance of the inclination sensor. In this report, we present an overview of the interim test for geometry errors, describe four methods of realizing the test, present performance evaluation data on a laser tracker from the different methods, and compare the methods in terms of their advantages and disadvantages.

Keywords

ASME B89.4.19; geometry errors; interim test; ISO 10360-10; laser tracker; performance evaluation.

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Acknowledgments

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1. Introduction

Laser trackers were first invented in the late 1980s and became more commonly used in the 1990s for manufacturing and assembly [1] of large structures. With increasing demand for a standardized set of test procedures to evaluate laser tracker performance, the B89.4.19 working group within ASME developed comprehensive test procedures to evaluate laser trackers resulting in the publication of the ASME B89.4.19-2006 [2] standard in 2006. The VDI/VDE 2634-10 (2011 version) [3] guideline and the ISO 10360-10:2016 [4] standard were later released in 2011 and 2016, respectively. The test procedures described in these standards (and guideline) are typically performed in a controlled laboratory environment by accredited laboratories and can take several hours to execute. While comprehensive testing of a laser tracker to assess conformance to specification is important for commerce, users of laser trackers often require quick and effective interim tests they can perform in the field to evaluate tracker health. The ASME 89.4.19-2006, ISO 10360-10:2016 and VDI/VDE 2634-10-2011 documents did include an interim test, but they were not comprehensive and were not sensitive to many geometric errors in laser trackers. See Table 1 for a summary of interim tests in these documents.

In response to this need for an effective interim test, the National Institute of Standards and Technology (NIST) developed a procedure that was outlined in an internal report, the NISTIR 8016 [5]. The test described in that report was designed to be sensitive to the different geometric errors in laser trackers. The procedure began to be widely used by industry and there were growing calls to incorporate that procedure into the Annex of both the ASME and ISO standards. In response to these calls, both the ASME B89.4.19 and ISO 10360-10 documents were opened for revision in mid-2010s and a new interim test was added into the Annex of both documents. There are two components to this new interim test – the first is a test to detect geometry errors based on the NISTIR 8016 report and the second is a test to assess performance of the inclination sensor developed within the ASME B89.4.19 working group. The updated documents, the ASME B89.4.19-2021 [6] and the ISO 10360-10:2021 [7] were both released in 2021 and include this new interim test. In this report, we describe the interim test to detect geometry errors (the inclination sensor test is not covered in this report), present four ways of realizing the test, and compare the methods in terms of their advantages and disadvantages.

Table 1. Interim tests in the ASME 89.4.19-2006, ISO 10360-10:2016 and VDI/VDE 2634-10-2011 documents.

ASME B89.4.19-2006	ISO 10360-10:2016	VDI/VDE 2634-10-2011
Diagonal length test with one nest at tracker height and another on the floor Two-face tests on targets in each of the two nests mentioned above	Two-face tests as described in the main body of the document Addition length tests are recommended but details not provided The network method described in Ref. [8]	Two-face tests Ranging direction length test Inside-outside test

2. Interim test for laser tracker geometry errors

2.1. Introduction

The proposed interim test for geometry errors includes both two-face and length measurement tests performed in the measurement volume of the laser tracker. The objective of the interim test is to assess the performance of the laser tracker in the presence of geometric or optical misalignments such as those occurring due to frequent packing, transport, and un-packing of a laser tracker. These causes of misalignments typically affect the geometry parameters of a laser tracker but do not affect the ranging unit. Thus, the ranging unit can be used for calibration of the reference artifact (such as a scale bar or a collection of fixed nests) used for this interim test of the laser tracker itself.

Table 2. Length test portion of the interim test.

Test #	Description	Figure 1 reference
1	Symmetrical length AC measured with the scale bar in the horizontal orientation, nest B at least 0.5 m above the laser tracker and the laser tracker at 0° azimuth when facing the center of the scale bar, and located at a distance *d* as close as practical (preferably 1 m) from the scale bar.	Position 1
2, 3	Asymmetrical lengths AB and BC for the conditions in Test # 1.	Position 1
4	Symmetrical length AC measured with the scale bar in the horizontal orientation, nest B at laser tracker height and the laser tracker at 0° azimuth when facing the center of the scale bar, and located at a distance *d* as close as practical (preferably 1 m) from the scale bar.	Position 2
5, 6	Asymmetrical lengths AB and BC for the conditions in Test # 4.	Position 2
7	Similar to Test # 4 but with the laser tracker at 90° azimuth when facing the center of the scale bar	Position 3
8, 9	Similar to Test # 5 and 6 but with the laser tracker at 90° azimuth when facing the center of the scale bar	Position 3
10	Symmetrical length AC measured with the scale bar in the vertical orientation, nest B at laser tracker height and the laser tracker at 90° azimuth when facing the center of the scale bar, and located at a distance *d* as close as practical (preferably 1 m) from the scale bar.	Position 4
11,12	Asymmetrical lengths AB and BC for the conditions in Test # 10.	Position 4
13	Symmetrical length AC measured with the scale bar in the vertical orientation, with the laser tracker at a user defined distance *d* from the scale bar, and any azimuth angle when facing the scale bar.	Position 5
14, 15	Asymmetrical lengths AB and BC for the conditions in Test # 13.	Position 5

The interim test is comprised of 15 two-face and 15 length tests as described in Tables 2 and 3, and Fig. 1. In this section, we describe the interim test using a three-nest scale bar. It is not required that a three-nest scale bar be used; different methods of realizing the test are described in the next sub-section. The three-nest scale bar shown in Fig. 2 has one nest (nest B) located at the center of the scale bar while the other two nests (nests A and C) are located at the ends. The length of the scale bar, which is the distance from nest A to nest C, should be at least 2.3 m.

Table 3. Two-face test portion of the interim test.

Test #	Description	Figure 1 reference
1, 2, 3	Two-face tests are performed on nests A, B, C which are located as described below. Nest B located at least 0.5 m above the laser tracker. Nests A and C located on either side of nest B, at least 1.15 m from nest B, so that nests A, B and C form a horizontal line that is orthogonal to the line joining the laser tracker and nest B. Laser tracker is at 0° azimuth when facing nest B and located at a distance *d* as close as practical (preferably 1 m) from the nest.	Position 1
4, 5 6	Two-face tests are performed on nests A, B, C which are located as described below. Nest B located at laser tracker height. Nests A and C located on either side of nest B, at least 1.15 m from nest B, so that nests A, B and C form a horizontal line that is orthogonal to the line joining the laser tracker and nest B. Laser tracker is at 0° azimuth when facing nest B and located at a distance *d* as close as practical (preferably 1 m) from the nest.	Position 2
7, 8, 9	Similar to Test # 4, 5 and 6, except that the laser tracker is at 90° azimuth when facing nest B	Position 3
10, 11, 12	Two-face tests are performed on nests A, B, C which are located as described below. Nest B located at laser tracker height. Nests A and C located above and below nest B, at least 1.15 m from nest B, so that nests A, B and C form a vertical line that is orthogonal to the line joining the laser tracker and nest B. Laser tracker is at 90° azimuth when facing nest B and located at a distance *d* as close as practical (preferably 1 m) from the nest.	Position 4
13, 14, 15	Similar to Test # 10, 11 and 12, except that the laser tracker is at a user defined distance *d* from the scale bar, and any azimuth angle when facing the scale bar.	Position 5

In Fig. 1, nest B is located directly in front of the tracker so that the line joining the tracker and nest B is orthogonal to the line joining the three nests A, B, and C. For all positions, length AC is at least 2.3 meters, and lengths AB and BC are nominally equal and at least 1.15 m. For positions 1, 2, and 3, nests A and C are located on either side of nest B so that the nests A, B, and C form a horizontal line. For positions 4 and 5, nests A and C are located above and below nest B so that the nests A, B, and C form a vertical line.

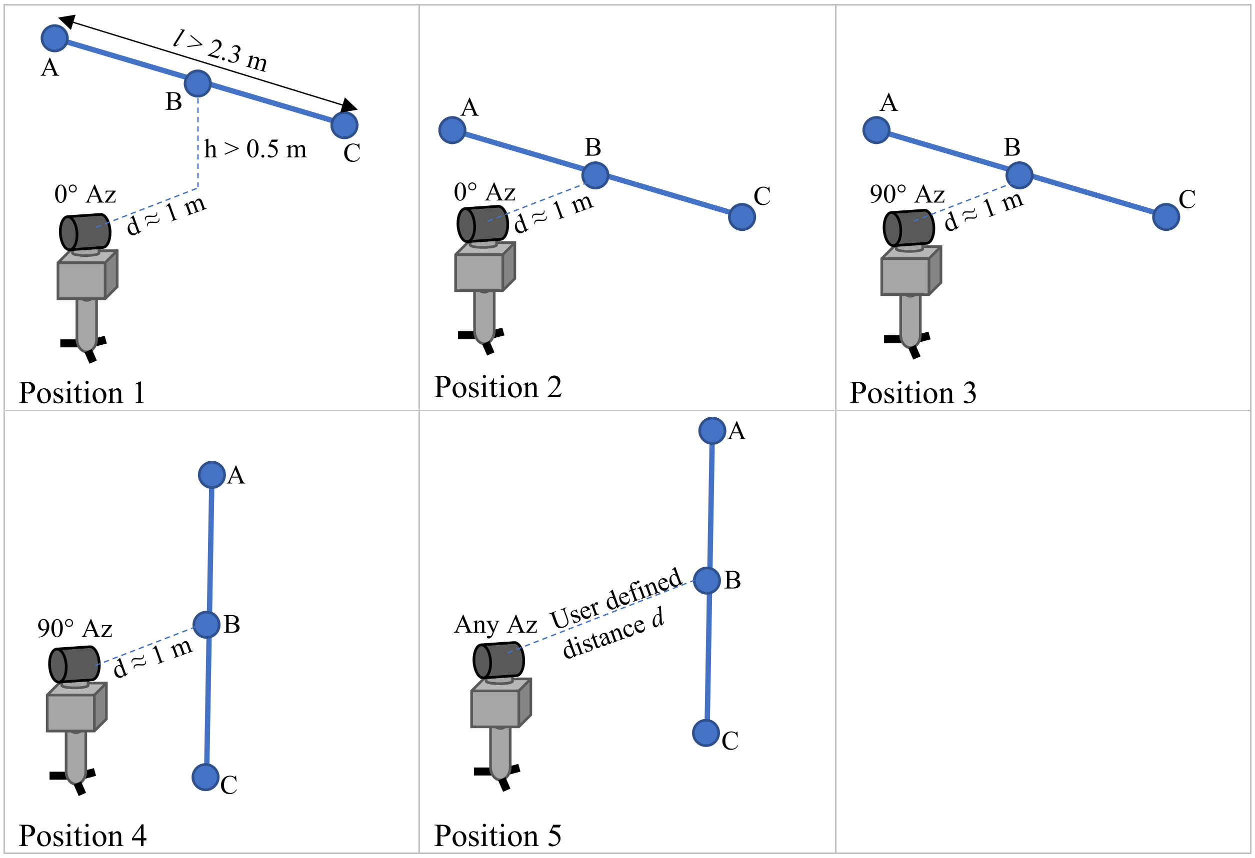


Fig. 1. Five test positions resulting in 15 length and 15 two-face tests.

Two-face errors are calculated for each of the nests, A, B, and C, and for each of the five positions in Fig. 1. Thus, 15 two-face errors are calculated in all. Length errors are calculated using measurements made in front-face only. For each of the five positions, one length error is obtained while measuring the symmetrical length AC while two length errors are obtained while measuring asymmetrical lengths AB and BC. Thus, 15 length errors are calculated in all. All 15 two-face errors and all 15 length errors should be smaller than the corresponding maximum permissible error (MPE) specifications. Errors larger than the MPEs indicate a problem with either the laser tracker or the test set-up (tripod, reference length, etc.). The source of the errors should be determined and resolved prior to using the laser tracker for measurements.

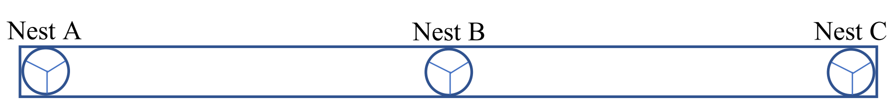


Fig. 2. Scale bar with three nests for interim testing.

2.2. MPE calculation

The MPE for the interim test may be specified by the user and does not necessarily have to be based on the manufacturer's specified values. Here, we calculated the MPEs for the tests based on accuracy specifications provided by the manufacturer in their brochures, and using the formula provided in ISO 10360-10:2021. We used the angular accuracy specification of 15 µm + 5 µm/m and ranging accuracy specification of 15 µm. For each of the length tests, we calculated MPE using the formula

$$MPE = [e_{R1}^2 \sin^2 \alpha_1 + e_{R2}^2 \sin^2 \alpha_2 + e_{R0}^2 (\sin \alpha_1 + \sin \alpha_2)^2 + e_{T1}^2 \cos^2 \alpha_1 + e_{T2}^2 \cos^2 \alpha_2]^{\frac{1}{2}} \quad (1)$$

where e_{R1} and e_{R2} are the MPEs for range measurement to targets 1 and 2, respectively, e_{R0} is the MPE of the R_0 error in the range (i.e., zero error), and e_{T1} and e_{T2} are the MPEs of the transverse errors to targets 1 and 2, respectively. See Fig. 3 for the geometry of the calculation.

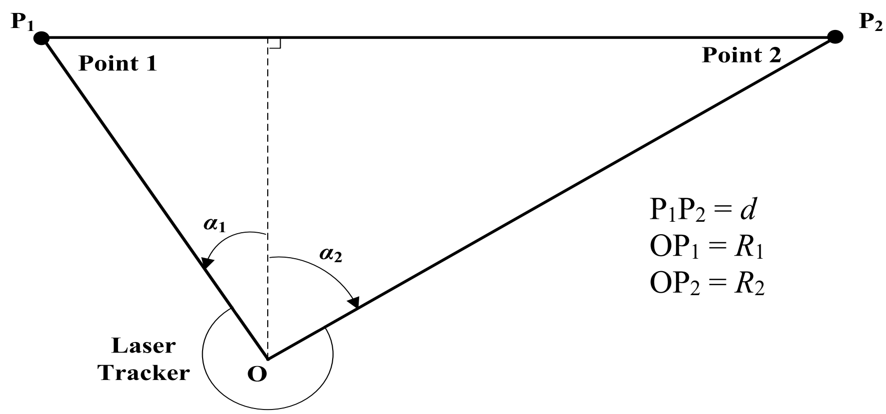


Fig. 3. Geometry for MPE calculation.

As an example, consider a specification of e_{R1}=e_{R2}=0.015 mm, e_{R0}=0, e_{T1}=0.015+0.005×R_1/1000, and e_{T2}=0.015+0.005×R_2/1000, where R_1 and R_2 are the distances (in millimeters) between the laser tracker and the ends of the length (Points P_1 and P_2), shown in Fig. 3. If the coordinates of Points P_1 and P_2 are known in Fig. 3, then the MPE of the length d can be calculated based on Eq. 1. For example, suppose the range, horizontal and vertical (zenith) angle to Point P_1 are 1355.236 mm, 172.947°, and 70.690°, respectively, and the range, horizontal and vertical angle to Point P_2 are 1750.546 mm, 134.698°, and 75.472°, respectively, then from the geometry, α_1 = 2.504°, and α_2 = 39.336°. From the manufacturer's specification, e_{R1} = 0.015 mm, e_{T1} = 0.022 mm, e_{R2} = 0.015 mm, and e_{T2} = 0.024 mm. Thus, the MPE for the length so positioned is 0.030 mm.

In the case of two-face errors, the MPE specification is twice the transverse specification, i.e., MPE = 2e_T. In this example, the MPE of the two-face error at Point P_1 is 2×0.022 = 0.044 mm and the MPE at Point P_2 is 2×0.024 = 0.048 mm.

2.3. Test value uncertainty

In order to decide whether a laser tracker has passed a conformance test, it is necessary to not only consider the measured error and the MPE, but also the uncertainty in the measured error, i.e., the test value uncertainty, against the MPE. This ratio of the MPE to test value uncertainty (expanded, $k = 2$), denoted by C_m, can be specified by the user in the case of the interim test. In the case of the length tests, the test value uncertainty is about 5 µm to 8 µm as mentioned in the next section, while the MPEs are generally about 25 µm to 50 µm, thus achieving a C_m of about 3 to 4. In the case of two-face tests, because the test involves essentially zero-length measurements made on a single, stationary retroreflector, the uncertainty in a two-face test is exceedingly small and therefore assumed to be zero.

3. Methods to realize the interim test

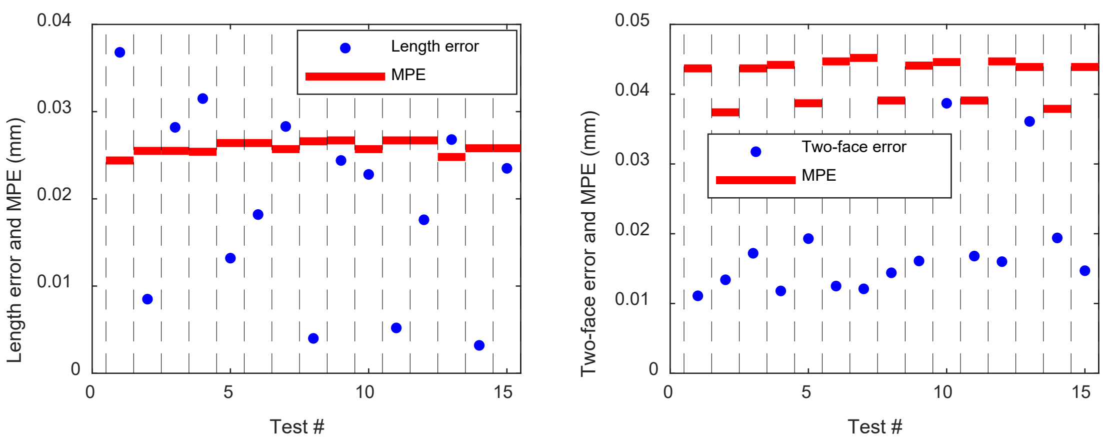
We describe four methods of realizing the interim test in this section. We describe both the concept and practical realization in our laboratory at NIST. The different methods were realized on different days and therefore the laser tracker under test was compensated prior to performing the interim test using the software provided by the manufacturer. Because the tests were performed on different days after new compensation, and the MPEs were slightly different (because of the relative positioning of the laser tracker with respect to the test artifact), we do not present the results from the different methods in a single chart as comparison is not particularly valid.

3.1. Using a three-nest scale bar

A 2.3 m three-nest scale bar such as described by Hudlemeyer et al. [9] is perhaps the easiest way to realize the interim tests. We realized the test at NIST using such a scale bar that had one central nest and one nest about 1.15 m away in either side. The scale bar was mounted so that it could be freely rotated about the central nest. Figs. 4 and 5 shows the scale bar in the horizontal and vertical position, respectively. The scale bar was calibrated using the tracker under test itself, and using a mirror mounted at one end of the scale bar, see [9, 10]. Hudlemeyer et al. [9] estimate the uncertainty in the calibrated length to be 7.9 µm ($k = 2$) for the 2.3 m length and 5.4 µm ($k = 2$) for the 1.15 m length. After calibration, we performed the interim test on the same tracker, the results are presented in Fig. 6. The results show that some length errors are larger than the MPE indicating the laser tracker might require compensation.

Fig. 4. Three-nest scale bar in the horizontal position.

Fig. 5. Three-nest scale bar in the vertical position.



(a) (b)

Fig. 6. Interim test results using a three-nest scale bar: (a) length errors and corresponding MPEs, (b) two-face errors and corresponding MPEs.

When using a three-nest scale bar, it is advantageous to acquire data using both faces of the tracker on all nests so that all two-face and length errors may be determined in one setting. Thus, in each of the five positions, the laser tracker measures the location of each SMR in front-face and again in back-face. Because the setup is optimized for the interim test, it took us less than 30 minutes to perform the entire test.

3.2. Using a two-nest scale bar

Two-nest scale bars may be used to measure all required two-face errors, symmetrical length errors and asymmetrical length errors that comprise the interim test procedure. If multiple two-nest scale bars are used, the scale bar used for the symmetrical length AC must be at least 2.3 m long while the scale bar used for the asymmetrical lengths AB and BC must be at least 1.15 m long. It is also permissible to use a single scale bar that is at least 2.3 m long for all length tests. Fig. 7 shows how a single scale bar (or the tracker) may be moved to realize one of the positions (Position 1) of the interim test. For the sake of convenience, the user may choose to measure the SMR at the ends of the scale bar in both faces at each of the three scale bar locations in Fig. 7. The user may then use only the front-face data to calculate the length error for the symmetrical length AC and the two length errors for the asymmetrical lengths AB and BC. However, the measured data allows the calculation of six two-face errors, which is more than the required number of three two-face errors. The user is then free to select one two-face error for each of the nest locations A, B, and C.

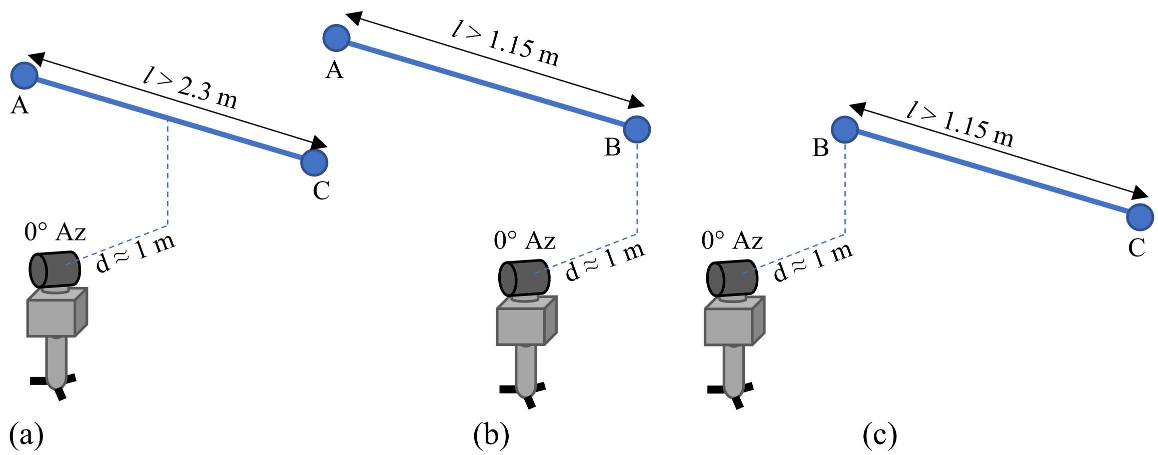


Fig. 7. Realizing Position 1 using a single scale bar by moving the laser tracker (or the scale bar), (a) scale bar located symmetrically with respect to the tracker to realize the symmetrical length AC, (b) laser tracker moved to the right to realize the asymmetrical length AB, (c) laser tracker moved to the left to realize the asymmetrical length BC. Note that while we use the label B in (b) and (c) for uniformity with the other sections, B is physically at the same location as nest C on the scale bar in (b) and nest A on the scale bar in (c).

At NIST, we have a 2.3 m long carbon fiber scale bar mounted on a rotary table that we have used in the past to calibrate laser trackers. The scale bar was calibrated in the line-of-sight method [11] using another tracker as shown in Fig. 8. The uncertainty in the calibrated length is 7 µm, $k = 2$ [12]. After calibration, we performed the interim test on a laser tracker using the scale bar as the reference standard. Because the scale bar can only be rotated but not translated, the laser tracker had to be physically moved to obtain the asymmetrical and symmetrical lengths for each horizontal position of the interim test. For the vertical positions, the laser tracker was placed on stands of different height to obtain the asymmetrical and symmetrical lengths. Fig. 9 shows the realization of the symmetrical raised horizontal length by placing the laser tracker on the floor. Fig. 10 shows the realization of the symmetrical vertical length. Fig. 11 shows the results from the interim test. Some length and two-face errors are larger than corresponding

MPEs indicating tracker may need compensation. Because we used a 2.3 m long scale bar for all length tests, including the asymmetrical lengths, there is higher sensitivity to geometry errors and therefore there is higher likelihood of errors exceeding MPEs if the tracker is not properly compensated. Because we had to move the laser tracker to many positions to complete the interim test, it took about two hours to complete the entire test.

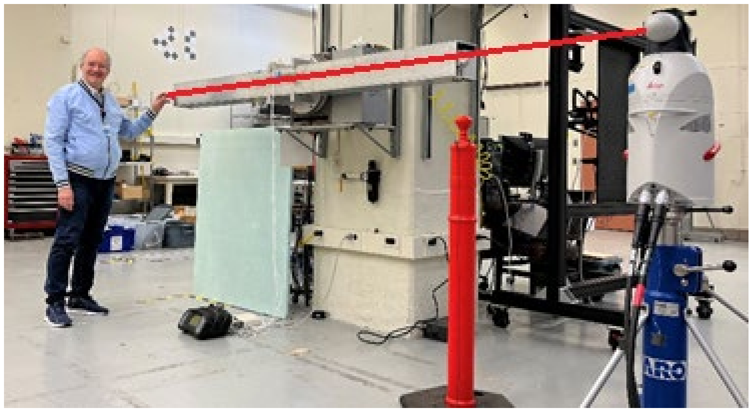


Fig. 8. Calibrating the two-nest scale bar using a laser tracker in line-of-sight method [11].

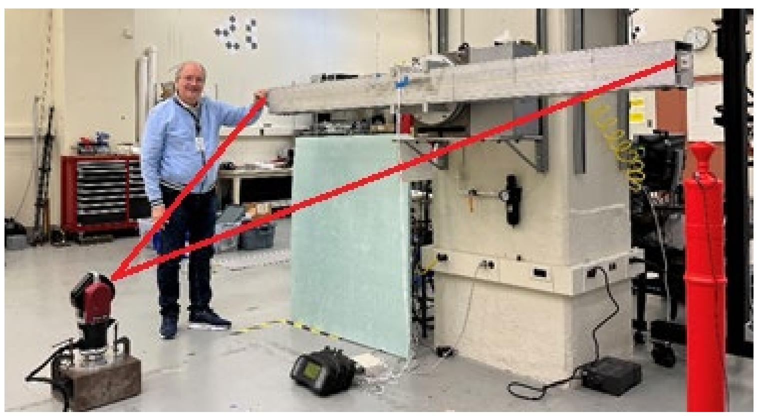
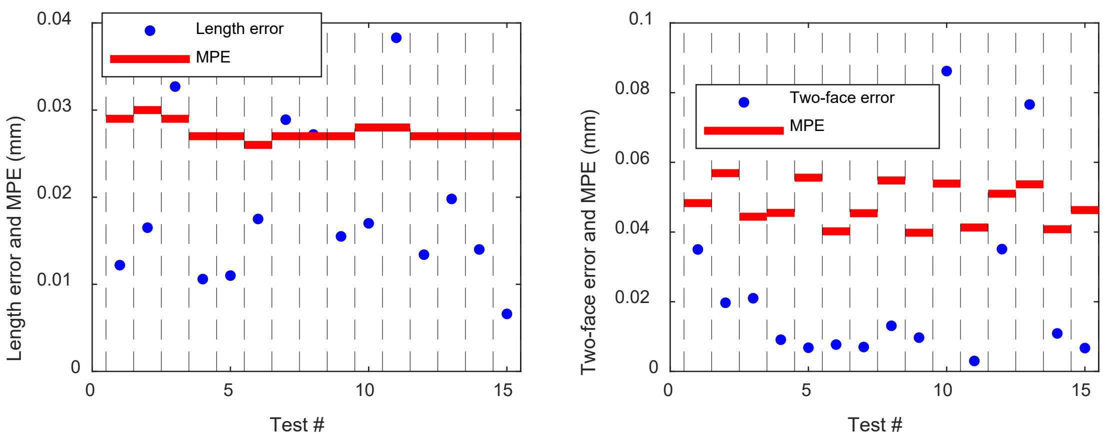


Fig. 9. Two-nest scale bar in raised horizontal position realized by placing the laser tracker on the floor.

Fig. 10. Two-nest scale bar in the vertical position.



(a) (b)

Fig. 11. Interim test results using a two-nest scale bar: (a) length errors and corresponding MPEs, (b) two-face errors and corresponding MPEs.

3.3. Using a half-scale bar

For users with limited resources, a single scale bar that is at least 1.15 m long can also be used to perform the interim tests as described here. The length errors and two-face errors corresponding to Position 1 in Fig. 1 may be realized as follows. The scale bar is first mounted as shown in Fig. 12(a) and the SMRs on nests A and B are measured in both faces. The scale bar is then rotated about nest B so that it is mounted as shown in Fig. 12(b). The SMR in nests B and C (while we use the label C for uniformity with the other sections, C is physically at the same location as nest A on the scale bar) are measured in both faces of the laser tracker. These measurements provide the necessary data to calculate the length error corresponding to the asymmetrical lengths AB and BC, and the two-face errors at nests A, B, and C. The length error for the symmetrical length

AC is simply the sum of errors for AB and BC. The tracker may then be raised so that it is at the same height as nest B and the scale bar rotated as needed to realize the other positions.

In our laboratory at NIST, we have a 1.15 m scale bar mounted on a bearing so that it can be rotated to construct an effective 2.3 m long reference length, see Lee et al. for details [13]. This scale bar was calibrated on a Cartesian coordinate measuring machine (CMM) with an uncertainty of 4.35 µm ($k = 2$) for the 1.15 m length and 8.7 µm ($k = 2$) for the 2.3 m length. This scale bar was then used to perform the interim test. Figs. 13 and 14 show the realization of the raised horizontal and vertical positions. Fig. 15 shows the results from the interim test. All length and two-face errors are within MPE specification. Using a half-scale bar to realize the interim tests is almost as efficient as using a three-nest scale bar. We were able to perform the tests in less than one hour using this method.

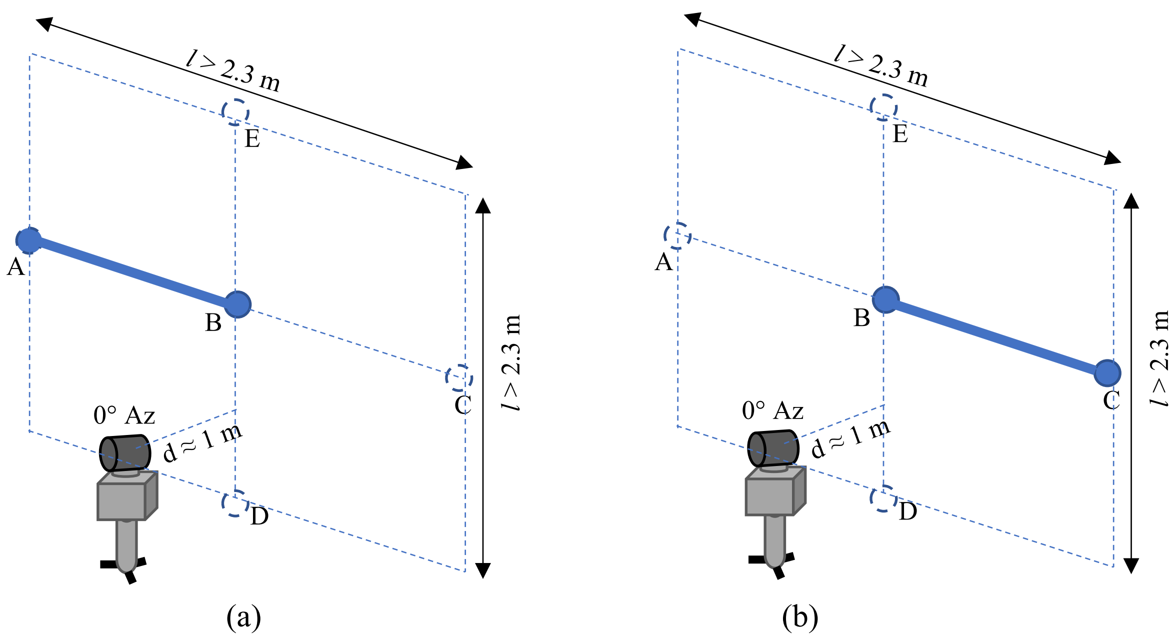


Fig. 12. Technique to realize interim test procedure using a single scale bar that is at least 1.15 m long, (a) scale bar mounted so that the laser tracker measures the SMRs located at nests A and B, (b) the scale bar is now rotated about nest B so that the laser tracker measures the SMR located at nests B and C. While we use the label C for uniformity with the other sections, C is physically at the same location as nest A on the scale bar.

Fig. 13. Half-scale bar in the raised horizontal position, (a) left half measurement (b) right half measurement.

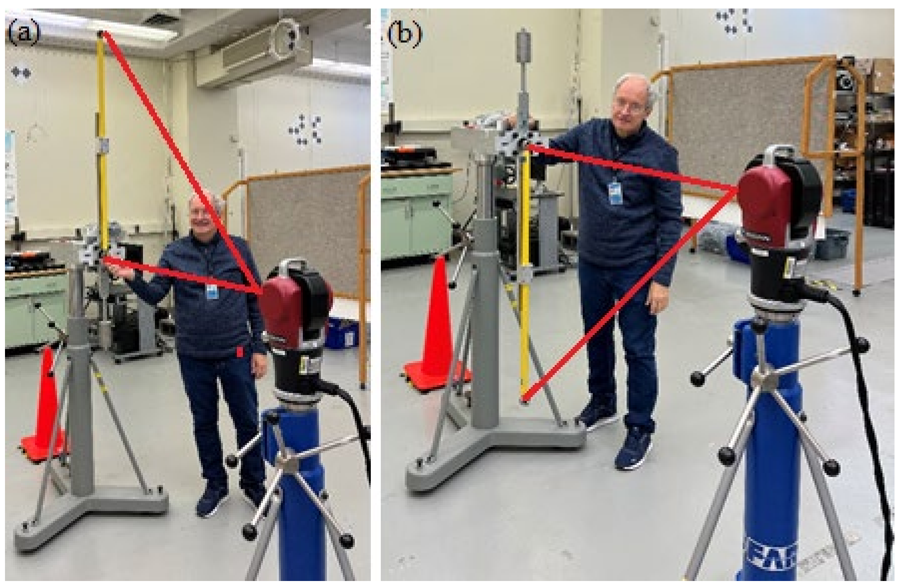
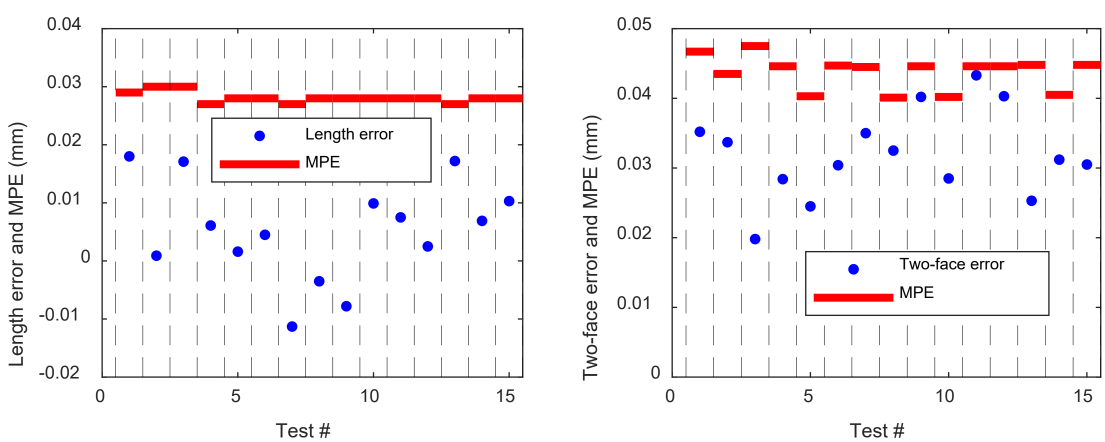


Fig. 14. Half-scale bar in the vertical position, (a) top half measurement (b) bottom half measurement.



(a) (b)

Fig. 15. Interim test results using a half-scale bar: (a) length errors and corresponding MPEs, (b) two-face errors and corresponding MPEs.

3.4. Using a stable grid of nests

The interim test procedure may also be realized using nests fixed to walls or other structures. Fig. 16 shows five nests mounted on a wall. The distances between the nests A, B, and C, and those between nests D, B, and E are assumed to be previously calibrated. As mentioned earlier in this report, the ranging unit of the laser tracker under test may itself be used for this calibration by careful alignment to minimize the angular motion of the tracker when moving an SMR along each of the two lines ABC and DBE. Position 1 is realized by placing the laser tracker about 1 m from the plane of the nests and about 0.5 m below nest B. The laser tracker may then be raised to the same height as nest B to realize the tests at other positions.

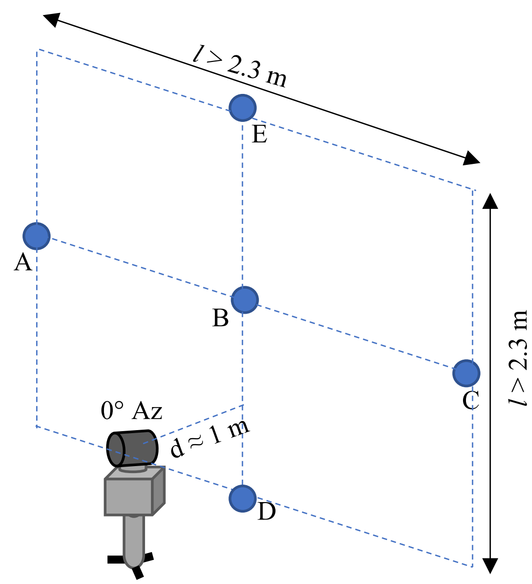


Fig. 16. Realizing interim test procedure using nests rigidly mounted to wall or other structures.

At NIST, we established a grid of nests on rigid vertical rails as shown in Fig. 17. We setup another laser tracker in-line with the horizontal nests to calibrate the distances between nests A, B, and C. Another laser tracker was used to calibrate the distances between nests D, B, and E, on the vertical line by using a mirror placed on the floor. The uncertainty in the calibrated length is less than 10 µm, $k = 2$. A detailed uncertainty budget is presented in Ref. [14], but all terms do not apply in this case because the measurement is quick and temperature variation is therefore not as much of a factor as was the case in Ref. [14]. We then performed the interim tests using these nests. The results are shown in Fig. 18. Some length errors are larger than MPE specifications indicating the tracker might require compensation. Using a grid of nests to realize the interim tests is almost as efficient as using a three-nest scale bar. We were able to perform the tests in less than one hour using this method. However, calibrating the grid of nests is a tedious and time-consuming process.

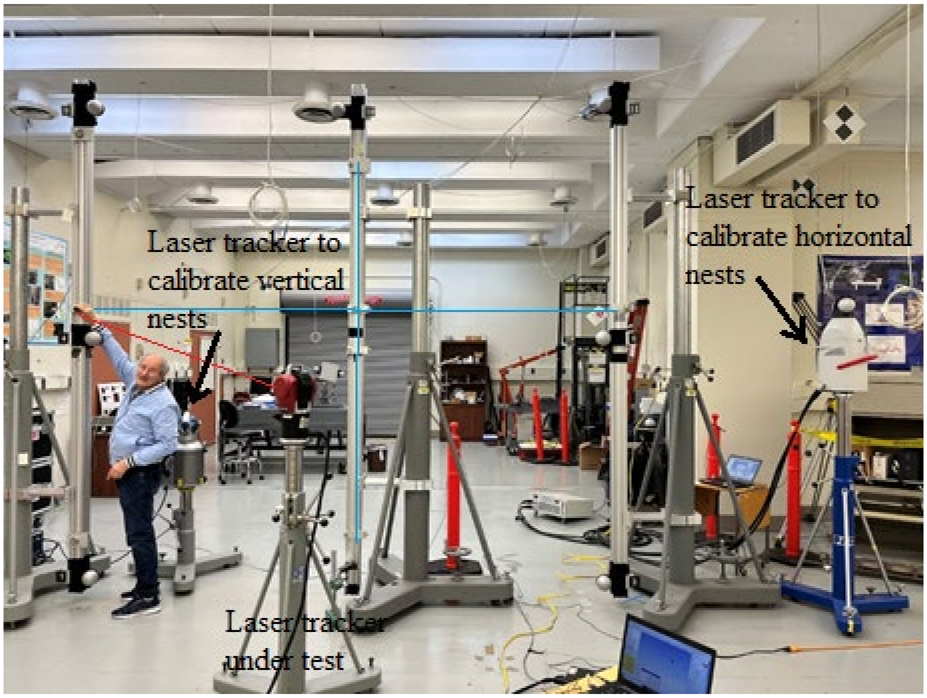


Fig. 17. Nests on vertical rails.

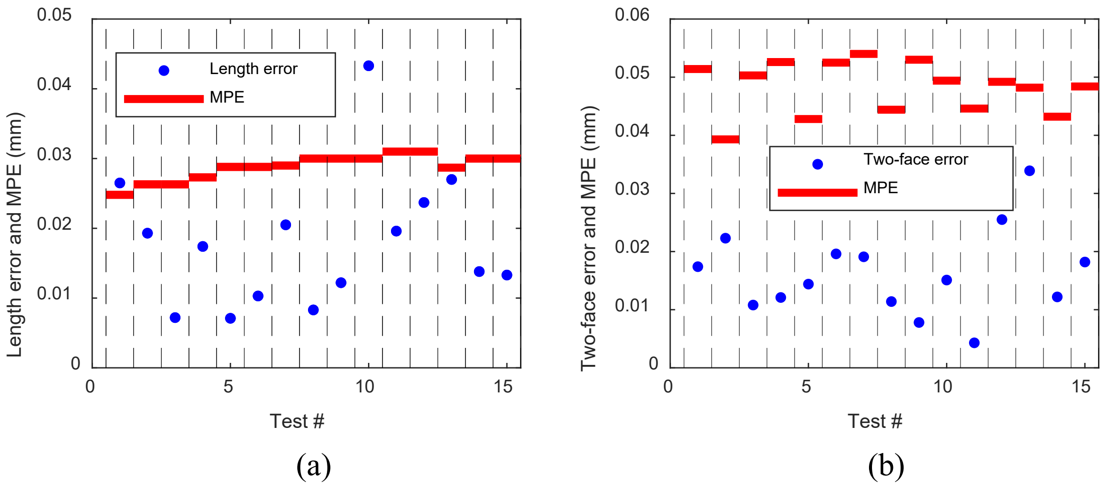


Fig. 18. Interim test results using a grid of nests: (a) length errors and corresponding MPEs, (b) two-face errors and corresponding MPEs.

4. Discussion and conclusions

In this report, we presented four ways of realizing the interim tests described in the newly revised ASME B89.4.19-2021 and ISO 10360-10:2021 standards. We summarize the advantages and disadvantages of the methods in Table 4.

Table 4. Advantages and disadvantages of the different methods.

	Advantages	Disadvantages
Three-nest scale bar	Quick and easy to perform the interim test Takes the shortest time among the methods considered here Requires no movement of the laser tracker	Cost of procuring the scale bar might be excessive for some users
Two-nest scale bar	If a single 2.3 m long scale bar is used for all positions including asymmetrical length tests, it provides considerably higher sensitivity to some geometric errors than a 1.15 m long asymmetrical length	Takes a long time to perform the test Requires moving the tracker to multiple locations to realize the symmetrical and asymmetrical positions
Half-scale bar	Reasonably quick to perform the test Minimal movement of tracker Potentially lower cost	Requires a CMM to calibrate the scale bar (at least in our realization)
Grid of nests	Reasonably quick to perform the test Minimal movement of the laser tracker	Takes a considerable effort to setup the nests, calibration can be tedious if an additional tracker is not available

Based on our experience with the four methods, the three-nest scale bar approach is the quickest and easiest way to realize the interim test. The half-scale bar approach is our second-best option but in our realization of that scale bar, a CMM is necessary to calibrate the bar, for our particular design. It is however possible to re-design the scale bar so that the laser tracker under test may be used for the calibration. The two-nest scale bar and grid of nests approach take a considerably longer time to execute.

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