Laser Tracker Testing at NIST in Accordance with the ASME B89.4.19 Standard

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Abstract

While the versatility and economics of laser trackers are quite appealing, the ability to assess their accuracy and to compare various brands has been limited by a lack of a national or international standard that encompasses testing and traceability procedures. This situation has now changed. In 2006, the American Society for Mechanical Engineers (ASME) board on Standardization and Testing approved the new B89.4.19 Standard - *Performance Evaluation of Laser-Based Spherical Coordinate Measurement Systems,* which appeared in print in January 2007. This Standard provides manufacturers and users with a common and well defined set of tests that can be performed to evaluate laser trackers and other spherical coordinate measurement systems that use cooperative targets. In this paper, we provide a brief overview of the B89.4.19 tests, describe our large scale facilities at the National Institute of Standards and Technology (NIST) and discuss some experimental results of B89.4.19 tests performed on commercial trackers.

1. Introduction

Spherical coordinate measuring machines (CMMs), such as interferometer (IFM) and absolute distance meter (ADM) based laser trackers, and other types of laser scanner systems are increasingly becoming more accurate and offer viable alternatives to more traditional CMMs. Their advantages include small size and portability, large measurement range and reduced capital costs. However, until recently, there was no national or international standard that defined the testing criteria for such instruments. Consequently, every manufacturer and customer created application specific tests resulting in confusion and unnecessary expense.

Several years ago, the B89 Committee, under the auspices of the ASME Board on Standardization and Testing, initiated the development of a standard that defined tests for evaluating the performance of laser trackers. This effort resulted in a new American standard, the ASME B89.4.19 - *Performance Evaluation of Laser-Based Spherical Coordinate Measurement Systems* [1], which is now in print and available through the ASME website at http://www.asme.org.

The B89.4.19 Standard describes performance tests for trackers that use a cooperative target such as a retroreflector. Typical IFM and ADM trackers therefore fall under the purview of this Standard. Laser scanners that function with non-cooperative targets are not currently covered by the Standard, however, some of these systems can use a tooling ball as a target (as a surrogate retroreflector) and hence can be specified to this Standard under this mode of operation. The B89.4.19 Standard explicitly ensures metrological traceability of the test results by the use of traceable reference lengths employed in the evaluation procedure. The traceable reference lengths satisfy the requirements of the B89.7.5-2006 Standard on *Metrological Traceability of Dimensional Measurements to the SI Unit of Length* [2].

At NIST's large scale metrology facility we have the capability of performing the complete set of tests as described in the B89.4.19 Standard. In this paper, we briefly review the performance tests, our facilities at NIST, and then discuss some results from B89.4.19 tests conducted on different trackers.

2. The ASME B89.4.19 Standard

The B89.4.19 Standard describes three kinds of tests to be performed on laser trackers: ranging tests, volumetric length tests, and two-face tests. More detail about the Standard's testing procedure can be found in [3].

The ranging tests assess the displacement measuring capability of the tracker along a purely radial direction. This test ties the ranging measurement system back to the SI unit of length, i.e., the meter. The horizontal and vertical rotation axes of the tracker remain stationary during this test in order to isolate the ranging errors of the tracker from other error sources.

Volumetric length tests are performed to assess the tracker's ability to measure different lengths within the work volume. Because a tracker may have several geometric errors in its construction, and these errors generally cannot be isolated, the orientations of the different volumetric lengths are chosen to sample a large spectrum of the horizontal and vertical angular encoder ranges to capture these errors effectively. In addition, these length measurements are performed at different distances from the tracker to sample the effects of radial position as well. The positions and orientations of these length measurements have been carefully chosen to be sensitive to both optical and mechanical tracker error sources. A well aligned or compensated tracker should be able to satisfy its Maximum Permissible Error (MPE) requirement, as specified by the tracker manufacturer. A tracker with misalignments can produce large errors and hence exceed its MPE. We illustrate both situations in later sections.

There are a number of geometric errors in a tracker that reverse in sign between front face and back face measurements (the back face measurement involves a 180 degree rotation about both the horizontal and vertical axes). Because most tracker measurements are conducted in front face mode only, these tests are useful in assessing the magnitude of those errors that are sensitive to back face measurement. Therefore, the B89.4.19 Standard describes a series of two-face tests for evaluating a tracker.

3. NIST Facilities

The Standard allows several methods for realizing the reference lengths used in the ranging test. At NIST we use our long length test facility with its 60 m laser rail and carriage system, see Figure 1. The tracker and a reference interferometer are located at the two opposite ends of the rail. A movable carriage on the rail carries two opposing retroreflectors, one for the tracker and another for the reference interferometer.

The reference interferometer has its vacuum wavelength calibrated against NIST's iodine stabilized laser. It is corrected in real time for the atmospheric index of refraction at an update rate of once per minute. The facility is maintained at 20 °C ± 0.2 °C. The pressure, temperature, and relative humidity sensors have expanded (k = 2) uncertainties of 20 Pa, 0.01 °C, and 1 % RH (relative humidity) respectively. Temperature sensors are located every 10 meters and a piecewise linear integration is

Figure 1. The NIST 60 m laser rail facility viewed from the tracker under test end; note the movable carriage with retroreflector.

used to evaluate the atmospheric correction along the beam path to the carriage position. The expanded (k = 2) uncertainty of reference length L is $U(L)$ = 5 µm + 0.3 × $10^{-6}L$.

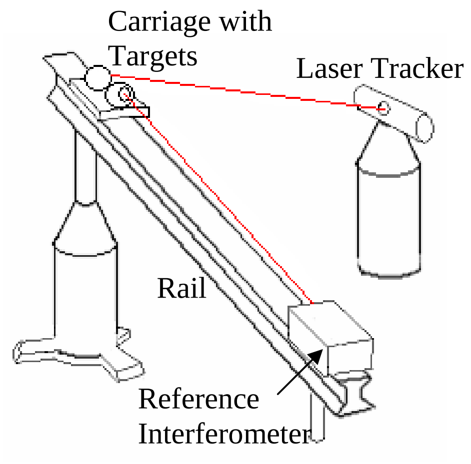

Figure 2. The LARCS laser rail.

We perform the complete set of volumetric and two face tests in our large scale metrology lab using a Laser Rail Calibration System (LARCS) [4]. The LARCS consists of a carriage and rails that can be mounted in different angular orientations to realize the horizontal, vertical and diagonal measurements as specified in the Standard. The carriage contains two retroreflectors, one for the reference interferometer and another for the tracker. The reference interferometer is also mounted on the rail, and the rail itself is sufficiently long to realize a 2.3 m reference length as required by the Standard. Figure 2 shows a schematic of the system. (Other methods of creating a reference length such as scale bars or calibrated fixed monuments are also allowed by the Standard.)

Figure 3. The NIST large scale facility; note horizontal rail to the left and vertical and inclined rail to the right.

For the LARCS system, the expanded uncertainty (k = 2) of a nominal reference length L is $U(L)$ = 3.4 µm + 0.5 × 10^{-6} L. Figure 3 shows the NIST facility.

Ranging Test Results

We have performed ranging tests on IFM and ADM based trackers. In Figure 4, we show the results from one such test of a tracker that has both an IFM and an ADM. The ranging test was repeated three times in accordance with the standard. We elected to include significantly more than the six required lengths for the ADM measurements in order to better describe the ranging error curve. This tracker clearly meets its manufacturer specified MPE requirements for both the IFM and ADM.

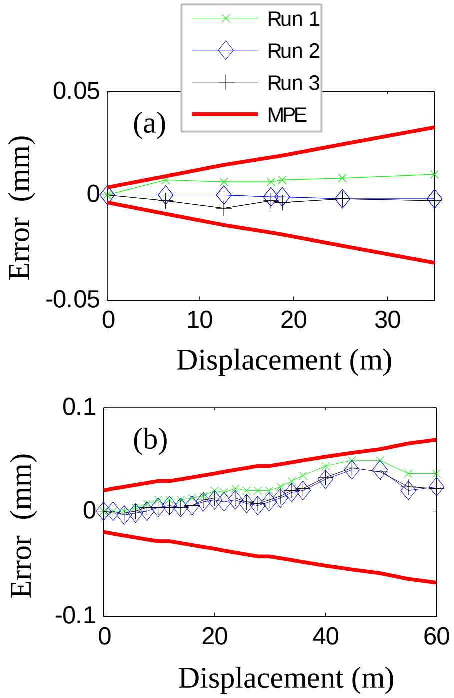

Figure 4. Ranging tests on a tracker; (a) IFM system (b) ADM system.

Helium-Neon laser interferometry is often considered the "gold standard" for displacement metrology. Hence, it is frequently thought that the only significant error source in the ranging system of an IFM tracker (excluding catastrophic failure) is associated with the atmospheric index of refraction, i.e., the weather station.

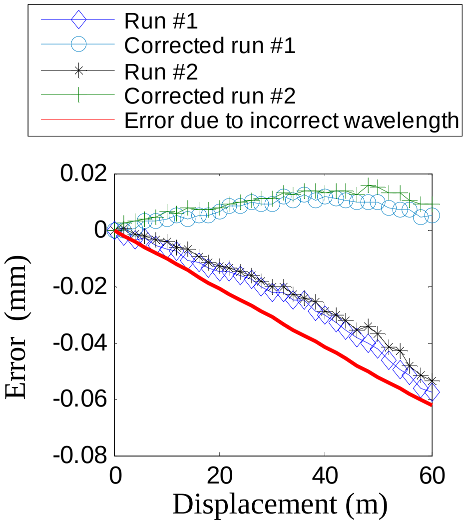

Figure 5. Ranging test of an IFM tracker.

Figure 5 shows IFM ranging data where atmospheric effects are largely removed by using a common index of refraction value for both the reference laser and the IFM tracker. Note that the system is in error by approximately 1 µm/m as shown by the "Run #1" and "Run #2" curves.

Further investigation revealed that the IFM internal vacuum wavelength was assigned a value of 632.990400 nm. Comparison against NIST's iodine stabilized laser determined a vacuum wavelength of 632.991061 nm. The relative difference (0.6 × 10^{-3} nm/633 nm) will result in a length error of approximately 1 µm/m, as shown by the solid curve in the figure. Correcting the IFM tracker's software to use the actual operating wavelength greatly reduces the observed error, as shown by the "corrected" data in the figure. Hence the use of the ranging test in a well controlled laboratory can reveal fundamental flaws in tracker ranging systems.

One possible explanation for this error is that the polarity of the wires used for laser cavity stabilization has been reversed. This would drive the laser to operate on a different cavity mode than expected; the magnitude of the observed wavelength error is consistent with this condition.

4. Volumetric Tests

In Figure 6 we show the results from the B89.4.19 volumetric performance tests on a tracker, along with the manufacturer's specified MPE values at each location. The measurements are partitioned according to the orientation of the reference length, i.e., horizontal, vertical, and right and left diagonals. Within each orientation group the measurements are

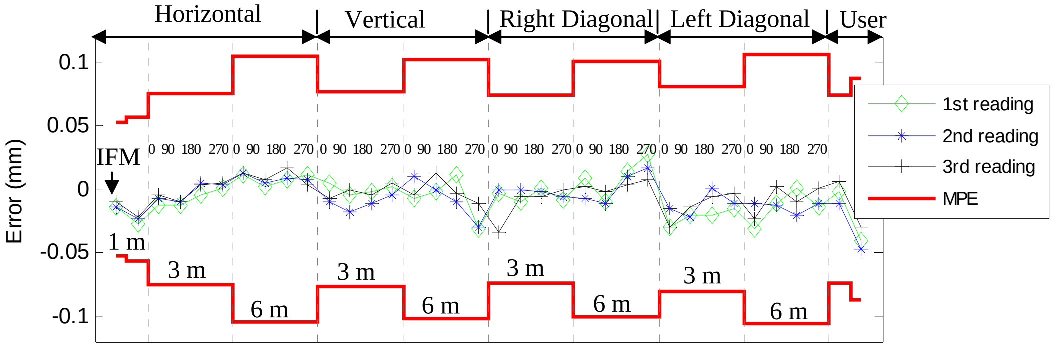

Figure 6. Volumetric performance test for an IFM/ADM tracker.

further partitioned by the distance from the tracker to the reference length. This is the distance "D" shown in Figure 7 for the case of a horizontal reference length; the value of D is typically 3 m or 6 m.

The first two measurements (at the extreme left in Figure 6) are errors in the measurement of a horizontal length with the tracker as close as possible to the reference length (this corresponds to "D" of approximately 1 m). The first point represents a length measurement made using the IFM of the tracker, while the second point represents a length measurement made using the ADM at the same location. All subsequent points in Figure 6 correspond to length measurements made using the ADM (see Alternate Test Method in Table 6 of the B89.4.19 Standard for trackers with an IFM and an ADM).

The remaining points in Figure 6 can be interpreted as follows. The tracker is located about 3 m from the horizontally oriented length such that the tracker's measured horizontal angle is 0° when the tracker is pointing at the center of the length, as shown in Figure 7. Three length measurements are performed at this location and orientation. The entire tracker is then rotated by 90° about the standing axis and three length measurements are performed again. This process is repeated for the 180° and 270° orientations of the tracker as well, generating sets of three errors (a measure of repeatability) at each angular orientation (0°, 90°, 180°, 270°). The tracker is then moved to a distance of 6 m from the horizontal length and the measurements are repeated as described above to generate sets of three errors at each angular orientation (0°, 90°, 180°, 270°) of the tracker.

A similar procedure is followed for the vertical length and the two diagonally oriented lengths. Finally, the two user selected (default) positions of the tracker are used to generate measurement errors and these are plotted at the far right of Figure 6.

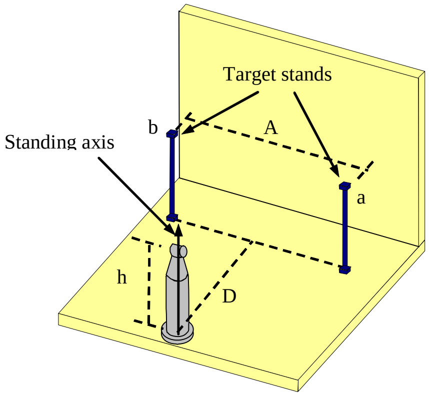

Figure 7. Horizontal length test, from [1].

There are a number of geometric misalignment terms that produce length errors that are dependent on the orientation of the tracker, such as encoder eccentricity, beam offset (in trackers with rotating mirror in the head), etc. There are other geometric terms that produce errors that depend only on the vertical angle of the beam, such as vertical encoder eccentricity. Other misalignment terms such as squareness between the two rotational axes affect diagonal length measurements. Finally, some of these terms produce length errors that scale inversely with distance "D".

The tests described above therefore are designed to capture these different geometric terms effectively by measuring lengths with different orientations (horizontal, vertical, along diagonals), at different radial distances from the tracker, and with different tracker orientations. While it is clear that the measured errors in Figure 6 are much smaller than the MPEs and therefore the tracker passes the volumetric portion of the B89.4.19 Standard, we also have examples of other trackers that did not pass the volumetric tests.

Figure 8 shows the results from the volumetric performance tests for another tracker. It is clear that some of the errors are much larger than the MPEs, and in addition, the errors are dependent on the orientation of the tracker. While this tracker does contain both an IFM and an ADM, the results shown here were obtained using the IFM. ADM data is expected to be marginally worse.

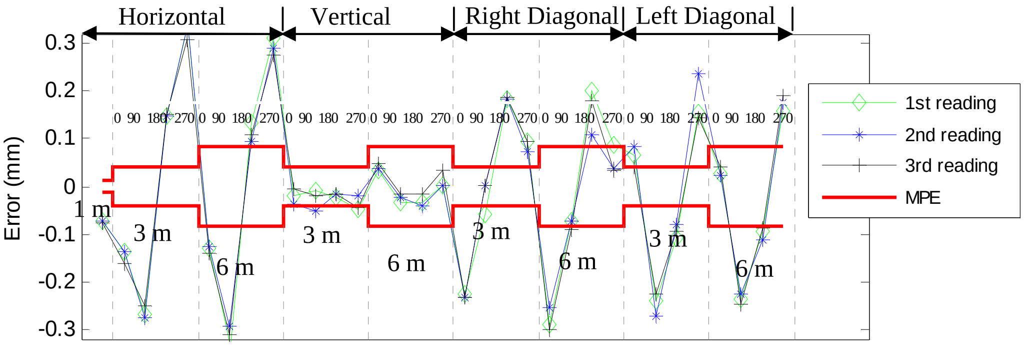

Figure 8. Volumetric performance test for another tracker.

While the ASME B89.4.19 Standard is not designed to be diagnostic in nature, it is possible to attempt an explanation for the observed behavior of these trackers, assuming such behavior is the result of some geometric error such as a misalignment, tilt or offset within the construction of the tracker. We have built mathematical models for each of these trackers, and these models can be used to simulate the effect of a specific error source on the ASME B89.4.19 tests. For example, four error sources, beam tilt along *X* and *Y*, and horizontal angle encoder eccentricity along *X* and *Y*,

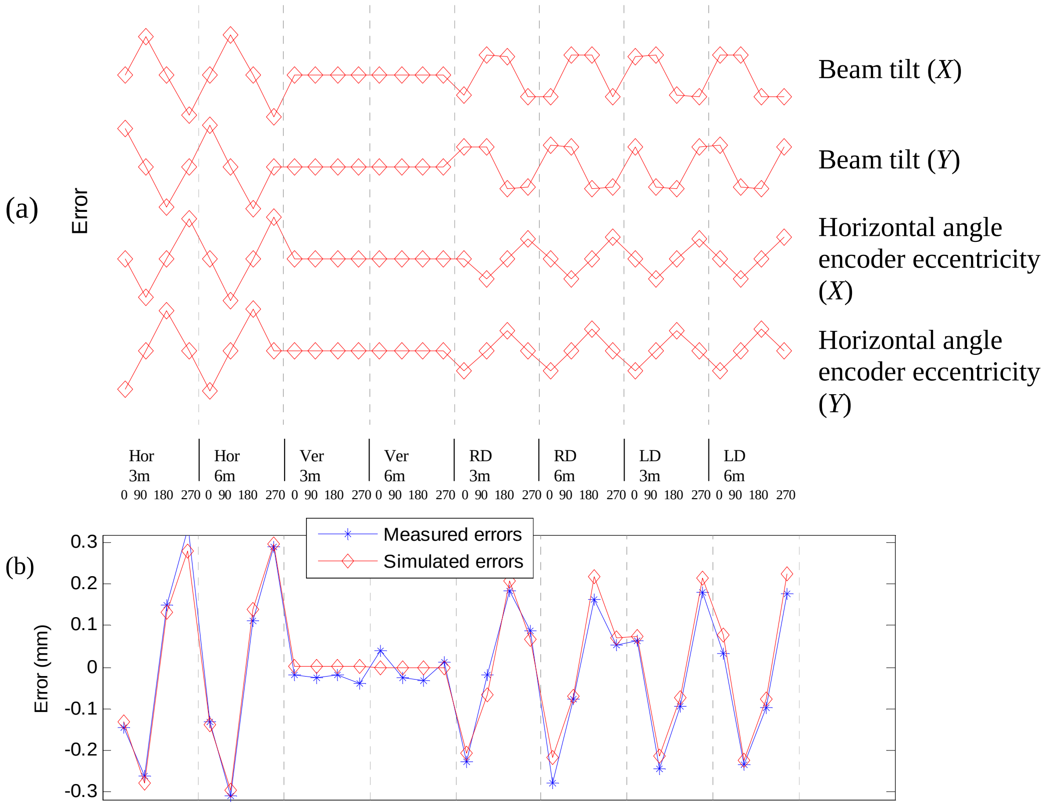

Figure 9. (a) The simulated effect of beam tilt and horizontal angle encoder eccentricity on the B89.4.19 volumetric length tests (b) The actual errors (average of the three runs shown in Figure 8) together with a linear combination of the simulated errors; the comparison shows good agreement.

individually produce an error pattern that resembles the observed volumetric error pattern in Figure 8; these errors are individually shown in Figure 9 (a). A linear combination of these terms, determined using a Least Squares best fit, captures the observed error pattern quite well, see Figure 9 (b), indicating that the source might in fact be the geometric terms identified above. Such analysis suggests that this tracker requires compensation; we have subsequently compensated the tracker and the B89.4.19 volumetric tests have shown dramatic improvement.

5. Two-Face Tests

There are a number of geometric error sources that change in sign between front face and back face measurements; common examples are the equivalent of a collimation error and transit tilt of a theodolite. While these errors change sign between front face and back face measurement and therefore their average cancel these effects, it is still necessary to test for the presence of these errors because not every measurement made using a tracker involves measuring a coordinate using both faces.

The two-face tests involve measuring a fixed target nest using both the front face and then the back face of the tracker and then computing the apparent distance between the measured points. This distance will be zero for an ideal tracker.

The B89.4.19 Standard requires such two-face tests to be performed on target nests located at three different heights: at ground level, at tracker level, and at twice the tracker height. The tracker is to measure each of these targets at three different distances: as close as possible, at 3 m, and at 6 m. At each height and distance The measurements are repeated three times and then the entire tracker is rotated by 90° about the standing axis and the process repeated until all four (0°, 90°, 180° and 270°) quadrants of the tracker orientation have been evaluated.

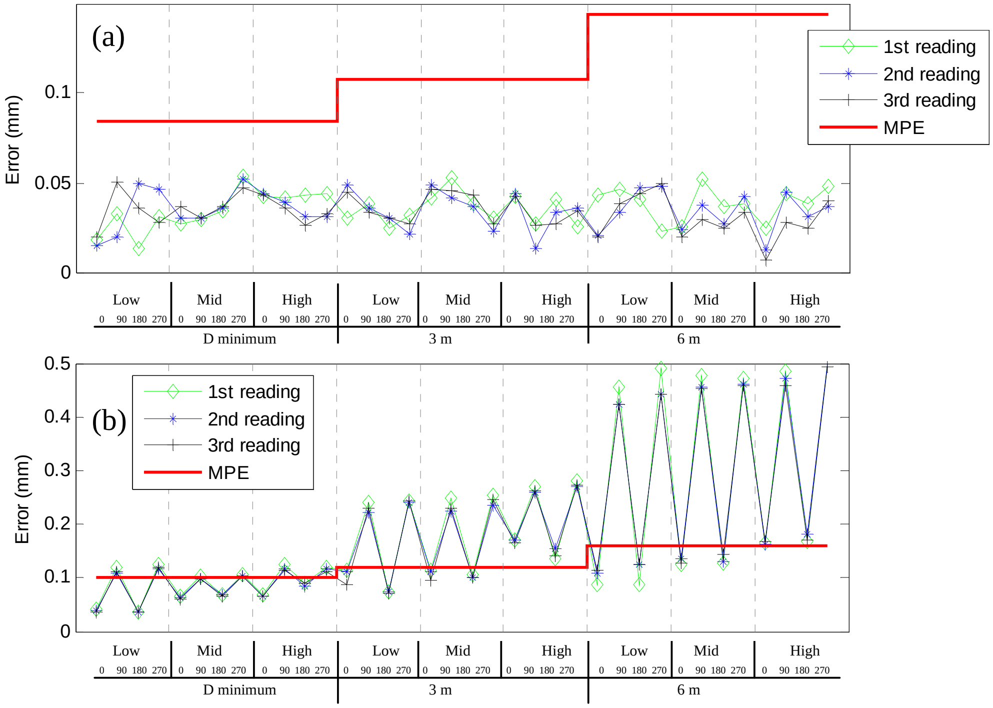

Figure 10. Two-face test results from two different trackers.

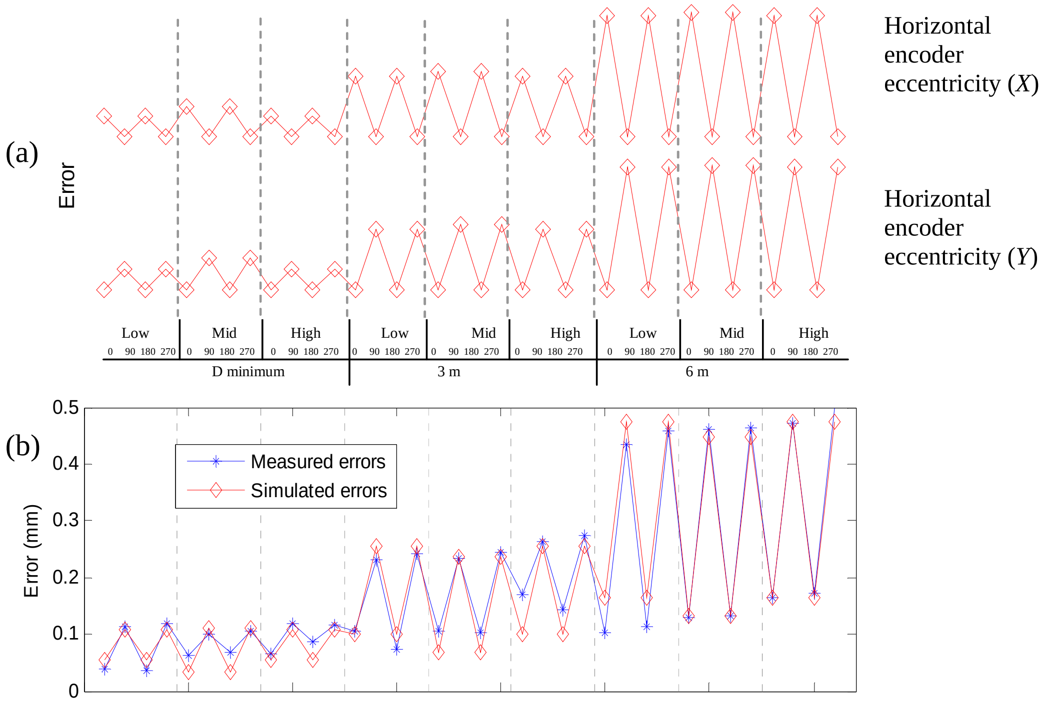

Figure 11. (a) Effect of horizontal angle encoder eccentricity on B89.4.19 two-face tests and (b) simulated errors (linear combination of encoder induced errors) and average of the three runs of measured errors showing good agreement.

Figure 10 shows the result of two-face tests conducted on two different trackers. The two-face test results for the tracker shown in Figure 10 (a) are well within its MPE specification. The other tracker, Figure 10 (b), shows large errors that are dependent on the orientation of the tracker. In addition, both the average errors and the amplitude of the triangular function are larger when the tracker is farther away from the target.

This observed error behavior is symptomatic of an eccentricity in the horizontal angle encoder. The magnitude of the error in the horizontal angle is a constant regardless of where the tracker is located. However, the length error is a function of both the horizontal angle error and the distance of the target from the tracker and therefore increases when the tracker is farther away. In addition, the length error is sensitive to the tracker's orientation about the standing axis. It is zero when the target is located along the line joining the center of the encoder and the true mechanical center of the standing axis and is largest when the target is along a normal to this line.

We have examined this using tracker models. Simulations suggest that the problem is likely due to an eccentricity of the horizontal angle encoder; see Figure 11.

6. Summary

The new ASME B89.4.19 Standard effectively captures many errors present in laser tracker systems. Use of the Standard will facilitate the testing and evaluation of tracker systems. This will allow both users and manufacturers to have a common set of testing procedures, facilitating both the interpretation and validation of laser tracker accuracy. Furthermore, issues associated with metrological traceability are explicitly addressed and are in compliance with the B89.4.7.5 Standard on dimensional measurement traceability.

In this paper, we have described ranging, volumetric and two-face tests conducted on commercial trackers as described in the B89.4.19 Standard. While some trackers did indeed pass these tests, results for others indicated a need for manual alignment or software compensation for geometric errors. While the Standard is not intended to be diagnostic, we have suggested here how the B89.4.19 tests in conjunction with tracker models can be utilized to understand the source of observed measurement errors.

Disclaimer

Data on commercial products are only provided for the sake of describing experimental results. NIST does not endorse or recommend any commercial products or imply that this equipment is the best for any particular application.

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