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Performance Evaluation of Laser-Based Spherical Coordinate Measurement Systems

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PERFORMANCE EVALUATION OF LASER-BASED SPHERICAL COORDINATE MEASUREMENT SYSTEMS

1 SCOPE

(21)

This Standard prescribes methods for the performance evaluation of laser-based spherical coordinate measurement systems and provides a basis for performance comparisons among such systems. Definitions, environmental requirements, and test methods are included with emphasis on point-to-point length measurements. The specified test methods are appropriate for the performance evaluation of a majority of laser-based spherical coordinate measurement systems and are not intended to replace more complete tests that may be required for special applications.

This Standard establishes requirements and methods for specifying and testing the performance of a class of spherical coordinate measurement systems called laser trackers.¹ A laser tracker is a system that directs the light from a range-measuring device to a retroreflecting target (called a retroreflector) by means of a two-axis rotary steering mechanism while monitoring the angular position of these rotary axes, thereby forming a spherical coordinate metrology system. Such a system may measure a static target, track and measure a moving target, or measure (and perhaps track) some combination of static and moving targets. This Standard can also be used to specify and verify the relevant performance tests of other spherical coordinate measurement systems that use cooperative targets, such as laser radar systems.

This Standard focuses specifically on the use of laser trackers as industrial measurement tools rather than on their use in surveying or geodesy. Specified tests are designed to evaluate the static point-to-point length measurement capabilities of these systems. The specified tests are not intended to evaluate the dynamic performance of the laser trackers. Additional tests are included that evaluate the range measurement capability of laser trackers equipped with absolute distance meters (ADMs). The tests do not evaluate workpiece thermal compensation capability and are not sensitive to spherically mounted retroreflector (SMR) imperfections.

2 INTRODUCTION

(21)

In addition to providing for the performance evaluation of laser trackers, this Standard facilitates performance comparisons among different systems by unifying the terminology and the treatment of environmental factors. It defines test methods appropriate for evaluating the performance of a majority of laser trackers, but it is not intended to replace more complete tests that may be required for special applications.

Systems that have passed the performance evaluation tests of this Standard are considered capable of producing traceable point-to-point length measurements for the conditions required herein. Application of point-to-point length measurements to a specific workpiece or measurement task may require additional testing and analysis in order to establish metrological traceability. This Standard provides technical guidance that may be useful in the calibration of laser-based spherical coordinate systems for point-to-point length measurements.

The Appendices describe various factors that should be considered when using this Standard.

(a) [Mandatory Appendix I](#) discusses metrological traceability, with particular focus on demonstrating traceability of reference lengths used in laser tracker performance evaluation. Requirements for demonstrating metrological traceability are presented per ASME B89.7.5.

(b) [Nonmandatory Appendix A](#) discusses the traceability of laser tracker point-to-point length measurements performed subsequent to a system passing the performance evaluation tests described in this Standard.

(c) [Nonmandatory Appendix B](#) describes tests and procedures for determining geometric errors in the construction of SMRs so that the suitability of a particular SMR for laser tracker performance testing can be evaluated.

(d) [Nonmandatory Appendix C](#) describes environmental factors that influence the refractive index of light in air. These factors affect the wavelength of light and should be carefully understood before proceeding with the tests described in this Standard.

¹ For purposes of this Standard, the terms *spherical coordinate measurement system* and *laser tracker* will be used interchangeably, notwithstanding the ability or inability to track a target.

(e) [Nonmandatory Appendix D](#) describes four methods that can be used to establish a calibrated reference length for point-to-point length measurement system tests. Uncertainties in realization of such lengths are discussed. [Nonmandatory Appendix D](#) also describes the measurement capability index and the simple 4:1 acceptance decision rule used to accept or reject laser tracker performance evaluation test results.

(f) [Nonmandatory Appendix E](#) describes the effects of spatial temperature gradients on laser beam propagation. Equations are derived for radial errors due to speed-of-light variations and angular (or transverse) errors due to beam refraction. A numerical example illustrates the use of the formulas.

(g) [Nonmandatory Appendix F](#) describes a number of interim tests that can be used to quickly assess laser tracker measurement performance in the interval between more complete performance evaluations.

This Standard prescribes performance evaluation tests that may be used by laser tracker manufacturers to generate performance specifications. These specifications are stated as the maximum permissible error (MPE) allowed for each test under specified environmental conditions.

Laser trackers may be tested against the manufacturer's specifications by using the performance evaluation tests described in [section 6](#). A typical test involves measuring a known reference length and comparing the observed error (laser-tracker-measured length minus reference length) with the specified MPE using a 4:1 simple acceptance decision rule per ASME B89.7.3.1-2001 (R2019). The reference length orientations and laser tracker positions in the evaluation have been chosen for their sensitivity to characteristic systematic errors known to occur in these systems.

Additional tests are included that characterize the consistency of the coordinates of a point when measured in both front-sight and back-sight modes. Both sets of tests have been designed to be easy to implement, fast, and simple to perform. The reference lengths used in the testing shall satisfy the traceability requirements of [Mandatory Appendix I](#). The summary test results shall be evaluated using the performance evaluation test procedures of [section 7](#) and reported on [Form 4-1](#).

While this Standard specifies the technical procedures for laser tracker specification and evaluation, it is the responsibility of the manufacturer and the customer to negotiate whether a particular system will be evaluated, what the cost will be, and where the evaluation will occur. Laser trackers that have successfully passed the performance evaluation (i.e., the system's measurement errors are not greater than the corresponding MPEs) are deemed capable of producing traceable point-to-point length measurements; see [Nonmandatory Appendix A](#).

While the tests described in this Standard characterize laser tracker point-to-point length measurement capability, such tests do not determine system-specific compensation parameters, which depend on the system-specific pointing mechanism. The performance evaluation tests emphasize the use of good metrology practice and simple fixtures. They stress the importance of measurement procedure details and that the measurement data are the result of the complete measuring system including the targets and probes.

(21) 3 DEFINITIONS

This section defines technical terms used in this Standard. Definitions quoted from JCGM 200:2012 include a parenthetical citation of the source. Definitions that do not include a parenthetical citation are specific to this Standard.

absolute distance meter (ADM): a laser tracker subsystem that emits light as a means to measure the absolute distance from a laser tracker to a remote target, usually a retroreflector.

NOTE: An ADM may also be referred to as an *electronic distance meter (EDM)*.

calibration: operation that, under specified conditions, in a first step, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication (JCGM 200:2012, definition 2.39).

cat's-eye: a type of retroreflector constructed from a glass sphere, or two or more concentric hemispheres, typically mounted in a spherical housing. See *retroreflector*.

compensation: the process of determining systematic errors of an instrument or system and then applying these values in an error model that seeks to eliminate or minimize measurement errors.

cube corner: also known as *corner cube*, a type of retroreflector constructed from three mutually orthogonal reflective surfaces that form an internal "corner"; it may be constructed of three plane mirrors or a trihedral prism. See *retroreflector*.

frontsight/back sight: these are modes of measurement. Frontsight is the normal measurement mode of the system. Backsight is obtained by rotating the laser tracker head about the vertical axis by 180 deg and then rotating the beam steering mechanism about the horizontal axis to again point at the target.

NOTE: Frontsight/back sight are sometimes referred to as direct/reverse or face 1/face 2.

home point: a location that is fixed relative to a laser tracker and accurately determined with respect to the origin of the laser tracker's coordinate system.

NOTES:

(1) The home point serves as a distance reference for the laser tracker's ranging devices.

(2) The home point is also sometimes referred to as the birdbath.

IFM: a laser tracker subsystem that uses displacement interferometer technology.

influence quantity: quantity that, in a direct measurement, does not affect the quantity that is actually measured, but affects the relation between the indication and the measurement result (JCGM 200:2012, definition 2.52).

limiting operating conditions: extreme operating condition that a measuring instrument or measuring system is required to withstand without damage, and without degradation of specified metrological properties, when it is subsequently operated under its rated operating conditions (JCGM 200:2012, definition 4.10).

NOTE: Manufacturer's performance specifications are not assured over the limiting operating conditions.

maximum permissible error (MPE): extreme value of measurement error, with respect to a known reference quantity value, permitted by specifications or regulations for a given measurement, measuring instrument, or measuring system (JCGM 200:2012, definition 4.26).

MPE_{ADM} : the MPE for a specified length measurement performed using the ADM as the laser tracker ranging subsystem.

MPE_{IFM} : the MPE for a specified length measurement performed using the IFM as the laser tracker ranging subsystem.

measurand: quantity intended to be measured (JCGM 200:2012, definition 2.3).

measurement capability index (C_m): the ratio of the MPE of a length measurement to the expanded test value uncertainty.

metrological traceability: property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty (JCGM 200:2012, definition 2.41).

rated operating conditions: operating condition that must be fulfilled during measurement in order that a measuring instrument or measuring system perform [sic] as designed (JCGM 200:2012, definition 4.9).

NOTES:

(1) Rated operating conditions generally specify intervals of values for a quantity being measured and for any influence quantity.

(2) In this document, rated operating conditions are also referred to as rated conditions.

[This definition, including [Note \(1\)](#), is identical to JCGM 200:2012, definition 4.9. [Note \(2\)](#) is specific to this Standard.]

reference length: the calibrated value of the distance between two points in space at the time and conditions when a test is performed.

refractive index, index of refraction (n): the ratio of the speed of light in a vacuum to the speed of light in a particular medium.

NOTE: In air, the refractive index is a function of the temperature, barometric pressure, relative humidity, and chemical composition of the air. Its effect must be compensated for when light is used to realize the meter (see [Nonmandatory Appendix C](#)).

refractivity (N): the ability of a substance to refract light expressed quantitatively as the value related to the refractive index, n , by the following equation: $N = (n - 1) \times 10^6$.

retroreflector: a passive device that reflects light parallel to the incident direction over a range of incident angles.

NOTE: Typical retroreflectors are the cat's-eye and the cube corner.

spherically mounted retroreflector (SMR): a retroreflector that is mounted in a spherical housing.

NOTE: In the case of an open-air cube corner, the vertex is typically adjusted to be coincident with the sphere center.

test value: the measurement error associated with a single indicated value of a system under test. The test value for a point-to-point length measurement test is the error in the measured length, and the test value for a two-face system test is the two-face error.

test value uncertainty: the uncertainty associated with a test value obtained during system verification.

NOTE: Because this Standard does not involve corrections to the indicated value (since testing is performed within the rated operating conditions and since there are no other corrections imposed by this test protocol), it is assumed that the uncertainty arising from the reference length is the only component of the test value uncertainty (see ASME B89.7.6).

transverse error: an error in the indicated position of a laser tracker target that is orthogonal to the line of sight.

two-face system test: a test that is performed to characterize certain geometric errors of the laser tracker.

NOTE: Frontsight/back-sight measurements are used in the two-face system test.

(21) 4 SPECIFICATIONS AND RATED CONDITIONS

Manufacturer's MPE specifications that conform to this Standard shall include completed [Form 4-1](#). Additionally, the manufacturer shall complete the relevant MPE specification columns in [Form 4-2](#). The manufacturer shall provide a formula or formulas for calculating the MPE that is applicable over the entire range of rated conditions as described in [Form 4-1](#). This may be separate formulas for calculating the MPEs for the length measurement system tests, the two-face system tests, and the ranging tests.

(21) 5 TEST ENVIRONMENT

The manufacturer shall specify the rated conditions of [section 4](#). If the user specifies that the performance evaluation test be performed in their facility, it shall be the responsibility of the user to provide an environment for testing the laser tracker that meets the manufacturer's rated conditions.

(21) 6 PERFORMANCE EVALUATION TESTS

This Standard specifies two types of performance evaluation procedures for laser trackers.

(a) *System Tests*. System tests are designed to evaluate the performance of a laser tracker in the measurement of a set of point-to-point lengths. For each point-to-point length, the test consists of comparing the length measured by the laser tracker with a known value called the reference length.

System tests are designed to exercise the laser tracker's ranging and angle measuring subsystems. The test length measurements are conducted at various locations and orientations with respect to the laser tracker and are chosen to be sensitive to known error sources of typical laser trackers. These measurements are augmented by two-face measurements, also conducted at a variety of locations and orientations, since many of the laser tracker's geometric errors are highlighted by this type of measurement. Detailed system test procedures are described in [paras. 6.2 and 6.3](#).

(b) *Ranging Tests*. Ranging tests are designed to evaluate a laser tracker's displacement (IFM) and/or distance (ADM) measuring devices. Because a laser tracker is a coordinate measuring system, it is important to test its ability to realize the unit of length (SI definition of the meter). Ranging tests are described in [para. 6.4](#).

6.1 General Requirements

The supplier shall be responsible for providing a laser tracker that meets the performance specifications of [section 4](#) when the system is installed and used according to the supplier's recommendations. The laser tracker shall include all necessary subsystems required to meet the specifications, i.e., all subsystems are considered part of the laser tracker and convey as part of the system under purchase. In particular, it is not permitted to employ special equipment (e.g., high accuracy barometers, thermometers, or SMRs) in the testing of the laser tracker that do not convey with the laser tracker. In the special case where the supplier requires the user to provide one or more subsystems as part of the purchase agreement, the supplier will state the subsystem specifications necessary to meet the laser tracker performance specifications of [section 4](#). The user shall accept a laser tracker that meets the performance specifications and any other conditions mutually agreed upon with the supplier. The criteria for meeting the performance specifications shall be the satisfactory completion of all required tests of [section 6](#), presentation of documentation of this result, and the appropriate documentation traceability of the reference length or lengths used during the testing.

Tests may be omitted only by mutual agreement between the supplier and customer. The particular tests required depend on the type of ranging subsystem incorporated in the laser tracker under evaluation. Specifically, laser trackers with an IFM only, an ADM only, or both an IFM and ADM require different tests that are sensitive to the unique error sources of these ranging subsystems.

**Form 4-2
Manufacturer's Performance Specifications and Test Results**

(21)

Test (Positions)	IFM Specifications and Test Results			ADM Specifications and Test Results		
	MPE _{IFM}	δ_{\max} OR Δ_{\max} [Note (1)]	Pass	MPE _{ADM}	δ_{\max} OR Δ_{\max} [Note (1)]	Pass
Horizontal (1)						
Horizontal (2, 3, 4, 5)						
Horizontal (6, 7, 8, 9)						
Vertical (1, 2, 3, 4)						
Vertical (5, 6, 7, 8)						
Right Diagonal (1, 2, 3, 4)						
Right Diagonal (5, 6, 7, 8)						
Left Diagonal (1, 2, 3, 4)						
Left Diagonal (5, 6, 7, 8)						
User Selected (1)						
User Selected (2)						
Two Face (1, 2, 3, 4)		[Note (2)]			[Note (2)]	
Two Face (5, 6, 7, 8)		[Note (2)]			[Note (2)]	
Two Face (9, 10, 11, 12)		[Note (2)]			[Note (2)]	
IFM Ranging Ref L (1) =		[Note (3)]				
IFM Ranging Ref L (2) =		[Note (3)]				
IFM Ranging Ref L (3) =		[Note (3)]				
IFM Ranging Ref L (4) =		[Note (3)]				
ADM Ranging Ref L (1) =						
ADM Ranging Ref L (2) =						
ADM Ranging Ref L (3) =						
ADM Ranging Ref L (4) =						
ADM Ranging Ref L User (1) =						
ADM Ranging Ref L User (2) =						
Formula for calculating the MPE or attach MPE specification sheet [Note (4)]						

Test Performed by: _____ Date: _____ Instrument Serial Number: _____
 C_m for IFM System Tests: _____ ; C_m for IFM Ranging Tests: _____ if $1 \leq C_m < 2$ Check "Low_ C_m "
 C_m for ADM System Tests: _____ ; C_m for ADM Ranging Tests: _____ if $1 \leq C_m < 2$ Check "Low_ C_m "
 Final Test Results (Pass/Fail): _____

GENERAL NOTES:

- (a) All units are in micrometers (μm).
- (b) The IFM columns must contain specifications and results for laser trackers with IFM only, the ADM columns must contain specifications and results for instruments with ADM only, and both pairs of columns must contain specifications and results for instruments with both an IFM and an ADM.
- (c) If an ADM result is used in place of an IFM result, the value should be placed in parentheses.

NOTES:

- (1) δ for length system results, Δ for two-face results; see paras. 7.1 and 7.2.
- (2) Two-face tests may be performed with either an IFM or an ADM.
- (3) These results can be results from long reference lengths, or computed from short reference lengths (see para. 7.3.1), or computed from the laser interferometer calibration certificate (see para. 7.3.1).
- (4) The manufacturer may specify separate MPE formulas for the system tests, ranging tests, and two-face tests.

**Table 6.1-1
Laser Tracker Performance Evaluation Requirements**

Laser Tracker Configuration	System Tests (Paras. 6.2 and 6.3)	Ranging Tests (Para. 6.4)
IFM only	All	IFM ranging test (para. 6.4.2)
ADM only	All	ADM ranging test (para. 6.4.3)
IFM and ADM	Default method:	Default method:
	All (using IFM ranging system)	IFM ranging test (para. 6.4.2)
	All (using ADM ranging system)	ADM ranging test (para. 6.4.3)
	Alternative method:	Alternative method:
	Horizontal length measurement system test, position 1 (para. 6.2.4) (using IFM and ADM ranging system)	IFM ranging test (para. 6.4.2)
	All (using ADM ranging system)	ADM ranging test (para. 6.4.3)

The specific tests that shall be performed for each laser tracker configuration are shown in Table 6.1-1. A system meets the manufacturer's performance specifications if the magnitude of the difference between each measured length and the corresponding reference length does not exceed the specified MPE. This acceptance criterion corresponds to a simple acceptance and rejection decision rule² with a stated measurement capability index, C_m (see Nonmandatory Appendix D).

The tests in this Standard evaluate the performance of a laser tracker relative to the manufacturer's MPE specifications for the measurement of point-to-point length under the stated rated conditions. The tests do not evaluate performance relative to other measurands or measurement conditions outside of the specified rated conditions.

6.2 Length Measurement System Tests

In a typical point-to-point length measurement system test, a laser tracker measures the distance between two points in space and the result is compared with a known value called the reference length. The reference length should be at least 2.3 m,³ and the expanded test value uncertainty, U , should not exceed one-fourth the MPE for the performance evaluation tests specified in para. 6.2 or one-half the MPE for the performance evaluation tests specified in para. 6.4. This corresponds to a measurement capability ($C_m = \text{MPE}/U$) equal to 4 and 2, respectively. (See Nonmandatory Appendix D, section D-2 for a discussion of C_m and its role in conformance decisions.)

6.2.1 Realization of the Reference Length. A traceable reference length (see Mandatory Appendix I) may be realized in a number of ways, including the following:

- (a) a calibrated artifact capable of holding retroreflectors near its ends (e.g., a scale bar)
- (b) two SMR kinematic nests mounted on independent freestanding rigid structures, with the distance between the nests calibrated by a distance or displacement measuring device
- (c) a rail and carriage system used in combination with an integrally mounted distance or displacement measuring device

Guidance for realizing a reference length by these methods, including a discussion of evaluating the test value uncertainty, is given in Nonmandatory Appendix D. In this Standard, it is assumed that the uncertainty arising from the reference length is the only component of the test value uncertainty.

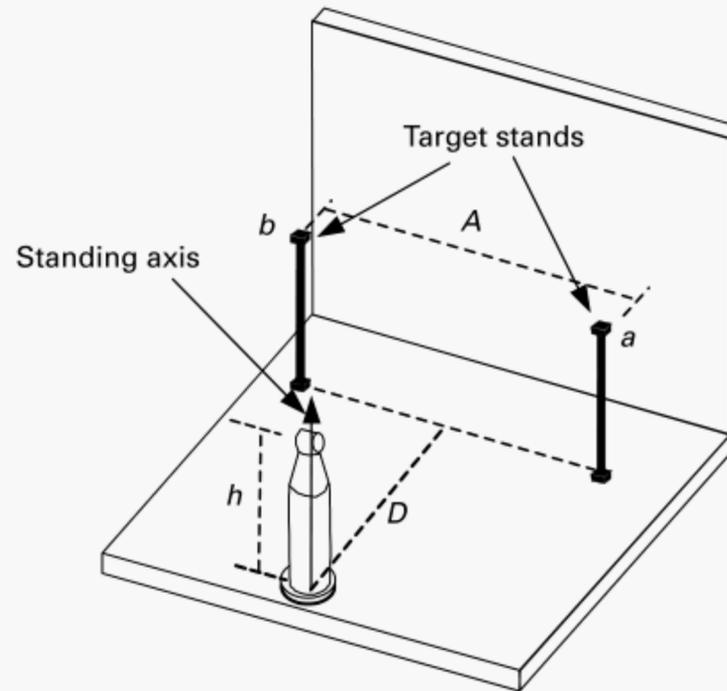
Paragraphs 6.2.4 through 6.2.7 detail the location and orientation of the reference length in each of the system tests. Paragraph 6.2.8 describes additional length measurement system tests that the user shall choose anywhere within the laser tracker working volume. It should be noted that the setups shown in the illustrations to Tables 6.2.1-1 through 6.2.1-4 show a reference length realized using two SMR kinematic nests as described in (b). If using a scale bar or laser rail, the setups will be different, although the location and orientation shall be the same.

6.2.2 Measurement Practices and Procedures. The following paragraphs describe practices and procedures that shall be followed when performing the tests described in this section. Several nonmandatory appendices provide more detailed information and supplemental guidance.

² Refer to ASME B89.7.3.1-2001 (R2019), para. 4.1.

³ The length of the artifact is a compromise between a long length to achieve test sensitivity and short length for manageability. The 2.3-m length has been shown to be a reasonable compromise that allows for practical utilization of the artifact.

Table 6.2.1-1
Horizontal Length Measurement System Test



Position Number	Distance, D (Approximate)	Measured Horizontal Angle to Target Nest a , deg
1	$0.1A$	Any
2	$1.2A$	0
3	$1.2A$	90
4	$1.2A$	180
5	$1.2A$	270
6	$2.7A$	0
7	$2.7A$	90
8	$2.7A$	180
9	$2.7A$	270

When measuring a reference length, test personnel should position the SMR or target in approximately the same orientation relative to the measurement beam. This minimizes the influence of geometric errors in the construction of the SMR or target on the length measurement system tests. (For information on SMR testing, see [Nonmandatory Appendix B](#).) A single SMR or target should be used to perform the length measurement system and ranging tests described in this Standard. SMR errors do not affect two-face system tests; therefore, multiple SMRs may be used for those tests. In the interest of reducing test time when using an ADM, manufacturers may, at their discretion, use more than one SMR. However, performing length measurements in this manner may significantly increase the length measurement errors for the tests performed.

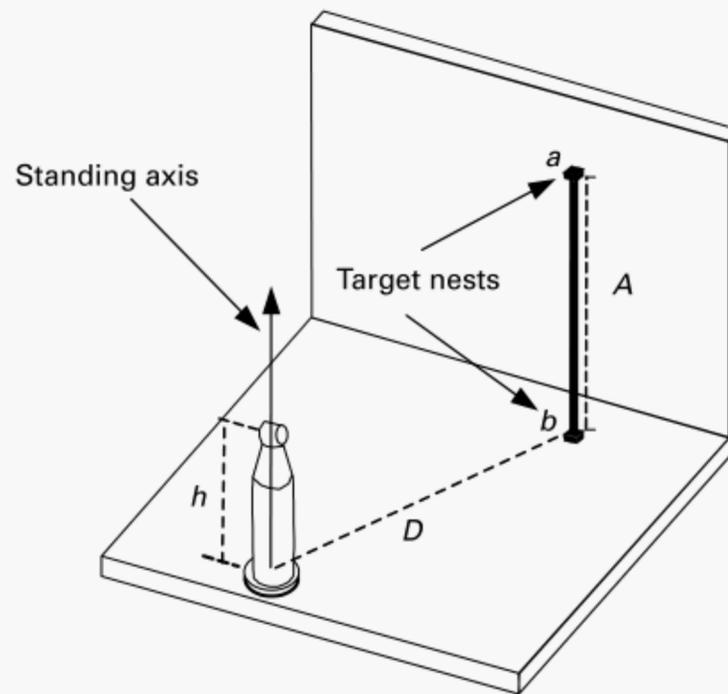
When performing a point-to-point length test, test personnel shall measure both ends of the reference length in the same face of the laser tracker, in either front-sight or back-sight mode. Although it is not required that all reference lengths be measured in the same face, it is desirable.

The test procedures are performed in prevailing laboratory temperature, which is likely not 20°C. The reference length and its uncertainty shall be made available at the prevailing laboratory temperature during testing.

If a physical artifact such as a calibrated scale bar is used to establish the reference length, the temperature of the artifact shall be monitored and recorded. In the likely event that the artifact is used in a test at a temperature different from the temperature at which it was calibrated, these data shall be used to adjust the value of the reference length for thermal expansion or contraction and its corresponding expanded uncertainty, as described in [Nonmandatory Appendix D](#). In other words, it is the reference length that is corrected for thermal influences during testing so that the measured error in the length may be compared against the MPE to determine conformance.

If the reference length is realized in situ (such as when employing freestanding structures or a rail and carriage system) using interferometry, the reference length calibration is performed in the prevailing laboratory thermal conditions. Therefore, no temperature correction for the reference length is required. However, the environmental conditions shall be monitored in order to correct for changes in the refractive index of air. Details for performing this calculation

Table 6.2.1-2
Vertical Length Measurement System Test



Position Number	Distance, D (Approximate)	Measured Horizontal Angle to Target Nests a and b , deg
1	$1.2A$	0
2	$1.2A$	90
3	$1.2A$	180
4	$1.2A$	270
5	$2.7A$	0
6	$2.7A$	90
7	$2.7A$	180
8	$2.7A$	270

are given in [Nonmandatory Appendix C](#). Typically, the software provided with commercially available displacement measuring interferometers has utility for performing this calculation and automatically compensating the laser wavelength.

6.2.3 Failure to Satisfy MPE Requirements. There are a total of 35 length measurement system test positions. At each position, the measurement shall be repeated three times. A maximum of five of the 35 length measurement test positions may have one, and only one, of the three values of the length measurement error outside of the conformance zone. If the laser tracker fails to meet the specification at more than five positions or has any test position with more than one of the three values outside the conformance zone, the laser tracker shall be compensated, repaired, or replaced, and the performance evaluation testing shall be repeated. If the laser tracker fails to meet the specification at one to five test positions, the following actions shall be taken:

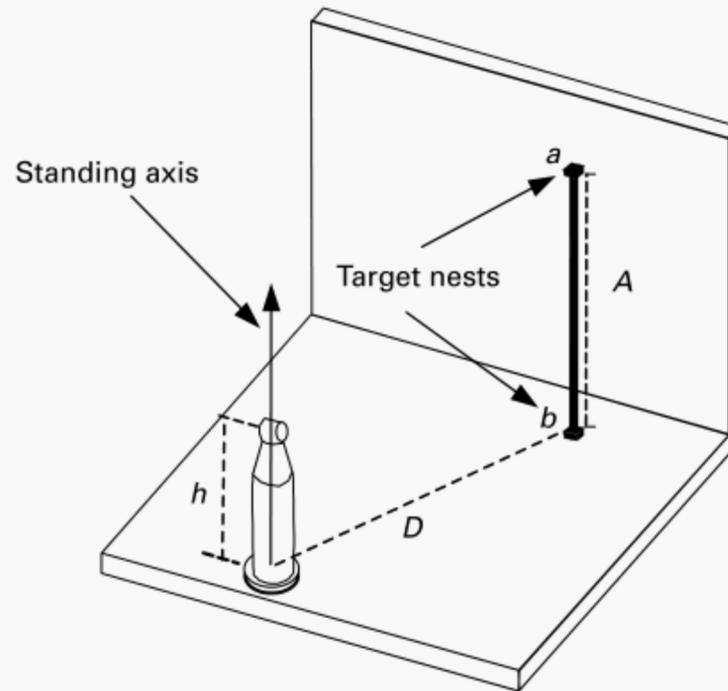
Step 1. Examine the reference length or lengths to assess stability and, if necessary, recalibrate the reference length or lengths. This is particularly relevant to [para. 6.2.1\(b\)](#), where drift in the location of the target nests can degrade the reference length.

Step 2. Remeasure the failed test position five times and select the largest absolute value of the five length errors (length error is the measured length minus the reference length) to replace the failed position value.

Step 3. If the new value satisfies the MPE requirement, then the laser tracker satisfies the requirement for the measurement at the failed test position, and testing can continue. If the new value fails to satisfy the MPE requirement, then [Steps 1](#) and [2](#) may be repeated a second time (but not more than twice), and if the laser tracker still exceeds the MPE, it fails the performance evaluation test. The system shall be compensated, repaired, or replaced, and the performance evaluation testing shall be repeated.

6.2.4 Horizontal Length Measurement System Tests. A horizontal reference length having target nests a and b is shown in the illustration in [Table 6.2.1-1](#). The distance A should be at least 2.3 m in length. The height h of the laser tracker should be approximately the same as the height of nests a and b . D represents the distance between the reference length

Table 6.2.1-2
Vertical Length Measurement System Test



Position Number	Distance, D (Approximate)	Measured Horizontal Angle to Target Nests a and b , deg
1	$1.2A$	0
2	$1.2A$	90
3	$1.2A$	180
4	$1.2A$	270
5	$2.7A$	0
6	$2.7A$	90
7	$2.7A$	180
8	$2.7A$	270

are given in [Nonmandatory Appendix C](#). Typically, the software provided with commercially available displacement measuring interferometers has utility for performing this calculation and automatically compensating the laser wavelength.

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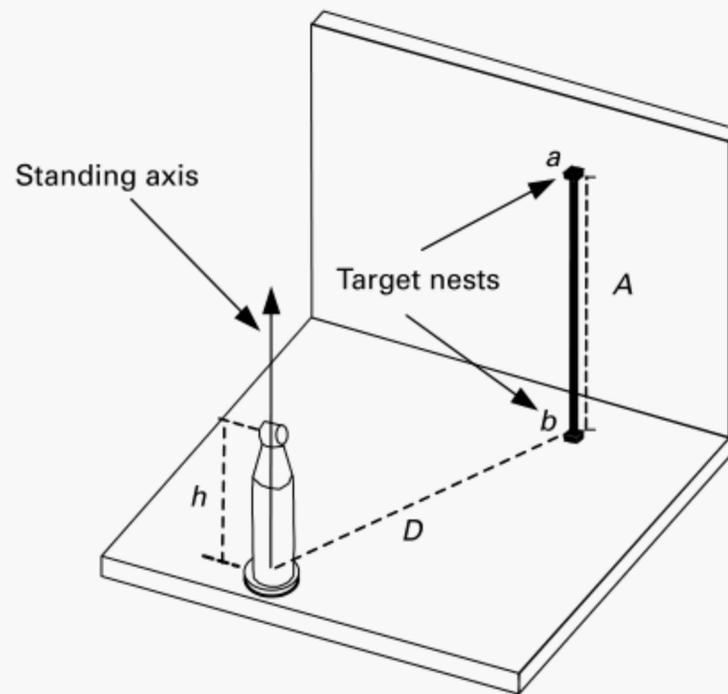
Step 1. Examine the reference length or lengths to assess stability and, if necessary, recalibrate the reference length or lengths. This is particularly relevant to [para. 6.2.1\(b\)](#), where drift in the location of the target nests can degrade the reference length.

Step 2. Remeasure the failed test position five times and select the largest absolute value of the five length errors (length error is the measured length minus the reference length) to replace the failed position value.

Step 3. If the new value satisfies the MPE requirement, then the laser tracker satisfies the requirement for the measurement at the failed test position, and testing can continue. If the new value fails to satisfy the MPE requirement, then [Steps 1 and 2](#) may be repeated a second time (but not more than twice), and if the laser tracker still exceeds the MPE, it fails the performance evaluation test. The system shall be compensated, repaired, or replaced, and the performance evaluation testing shall be repeated.

6.2.4 Horizontal Length Measurement System Tests. A horizontal reference length having target nests a and b is shown in the illustration in [Table 6.2.1-1](#). The distance A should be at least 2.3 m in length. The height h of the laser tracker should be approximately the same as the height of nests a and b . D represents the distance between the reference length

Table 6.2.1-2
Vertical Length Measurement System Test



Position Number	Distance, D (Approximate)	Measured Horizontal Angle to Target Nests a and b , deg
1	$1.2A$	0
2	$1.2A$	90
3	$1.2A$	180
4	$1.2A$	270
5	$2.7A$	0
6	$2.7A$	90
7	$2.7A$	180
8	$2.7A$	270

are given in [Nonmandatory Appendix C](#). Typically, the software provided with commercially available displacement measuring interferometers has utility for performing this calculation and automatically compensating the laser wavelength.

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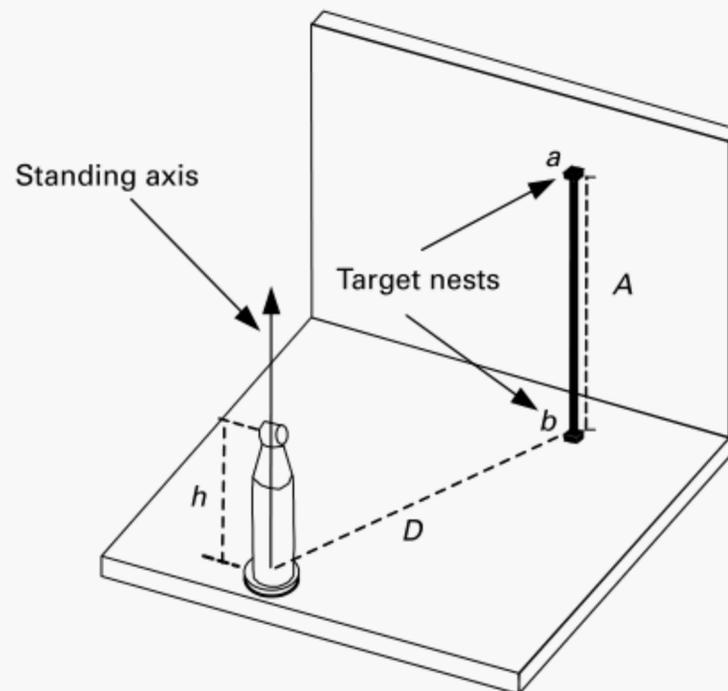
Step 1. Examine the reference length or lengths to assess stability and, if necessary, recalibrate the reference length or lengths. This is particularly relevant to [para. 6.2.1\(b\)](#), where drift in the location of the target nests can degrade the reference length.

Step 2. Remeasure the failed test position five times and select the largest absolute value of the five length errors (length error is the measured length minus the reference length) to replace the failed position value.

Step 3. If the new value satisfies the MPE requirement, then the laser tracker satisfies the requirement for the measurement at the failed test position, and testing can continue. If the new value fails to satisfy the MPE requirement, then [Steps 1 and 2](#) may be repeated a second time (but not more than twice), and if the laser tracker still exceeds the MPE, it fails the performance evaluation test. The system shall be compensated, repaired, or replaced, and the performance evaluation testing shall be repeated.

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Table 6.2.1-2
Vertical Length Measurement System Test



Position Number	Distance, D (Approximate)	Measured Horizontal Angle to Target Nests a and b , deg
1	$1.2A$	0
2	$1.2A$	90
3	$1.2A$	180
4	$1.2A$	270
5	$2.7A$	0
6	$2.7A$	90
7	$2.7A$	180
8	$2.7A$	270

are given in [Nonmandatory Appendix C](#). Typically, the software provided with commercially available displacement measuring interferometers has utility for performing this calculation and automatically compensating the laser wavelength.

6.2.3 Failure to Satisfy MPE Requirements. There are a total of 35 length measurement system test positions. At each position, the measurement shall be repeated three times. A maximum of five of the 35 length measurement test positions may have one, and only one, of the three values of the length measurement error outside of the conformance zone. If the laser tracker fails to meet the specification at more than five positions or has any test position with more than one of the three values outside the conformance zone, the laser tracker shall be compensated, repaired, or replaced, and the performance evaluation testing shall be repeated. If the laser tracker fails to meet the specification at one to five test positions, the following actions shall be taken:

Step 1. Examine the reference length or lengths to assess stability and, if necessary, recalibrate the reference length or lengths. This is particularly relevant to [para. 6.2.1\(b\)](#), where drift in the location of the target nests can degrade the reference length.

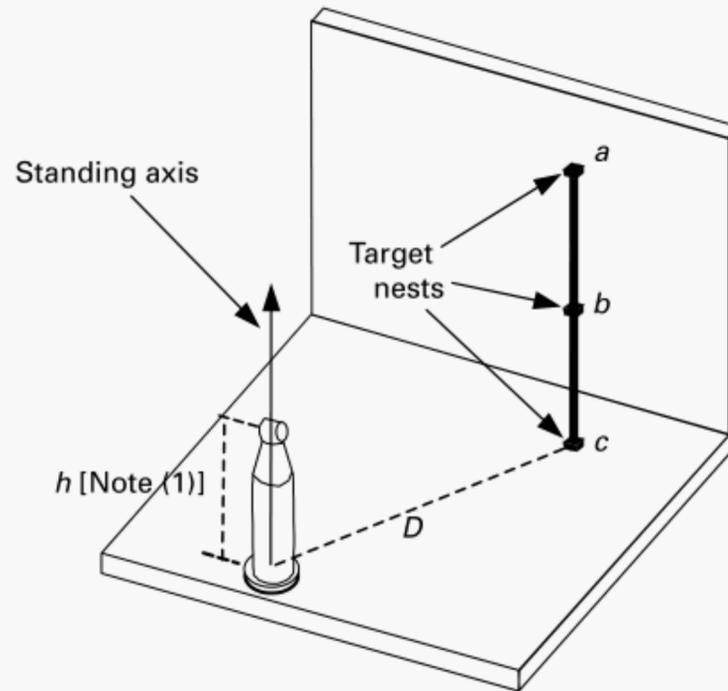
Step 2. Remeasure the failed test position five times and select the largest absolute value of the five length errors (length error is the measured length minus the reference length) to replace the failed position value.

Step 3. If the new value satisfies the MPE requirement, then the laser tracker satisfies the requirement for the measurement at the failed test position, and testing can continue. If the new value fails to satisfy the MPE requirement, then [Steps 1 and 2](#) may be repeated a second time (but not more than twice), and if the laser tracker still exceeds the MPE, it fails the performance evaluation test. The system shall be compensated, repaired, or replaced, and the performance evaluation testing shall be repeated.

6.2.4 Horizontal Length Measurement System Tests. A horizontal reference length having target nests a and b is shown in the illustration in [Table 6.2.1-1](#). The distance A should be at least 2.3 m in length. The height h of the laser tracker should be approximately the same as the height of nests a and b . D represents the distance between the reference length

Table 6.3.1-1
Two-Face System Test

(21)



Position Number	Distance, D (Approximate)	Measured Horizontal Angle to Target b , deg
1	[Note (2)]	0
2	[Note (2)]	90
3	[Note (2)]	180
4	[Note (2)]	270
5	3 m	0
6	3 m	90
7	3 m	180
8	3 m	270
9	6 m	0
10	6 m	90
11	6 m	180
12	6 m	270

NOTES:

(1) The height h should be at least 1 m.(2) Minimize D in order to maximize the vertical angular range of motion between nests a and c .

6.4 Ranging Tests

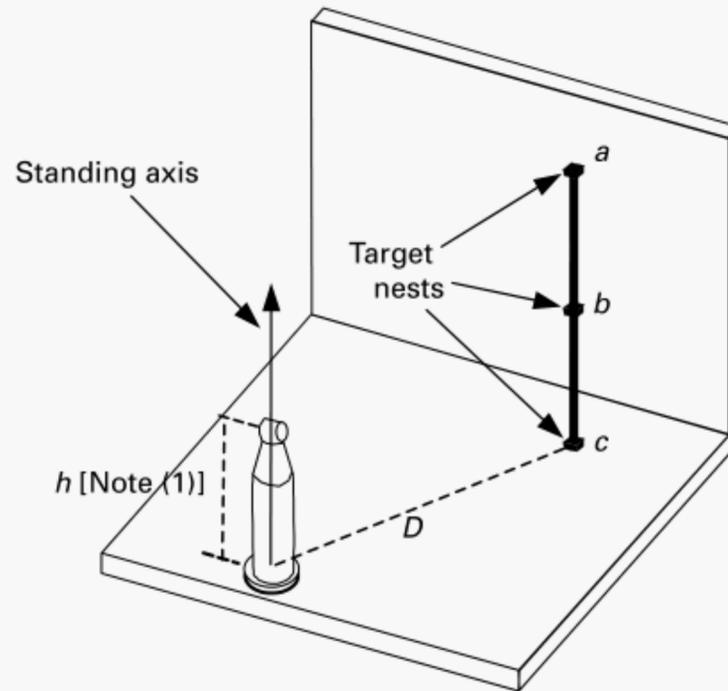
In a typical ranging test, the laser tracker measures the distance between two points in space that are nominally along a radial (ranging) direction of the tracker, and the result is compared to the reference length. For IFMs, the ranging test may be performed with long reference lengths or short reference lengths. For ADMs, only long reference lengths are used. Instead of performing a ranging test by measuring the distance between two points, IFMs may be tested for conformance by performing a wavelength calibration. Only one measurement of each position is required for the ADM and IFM long reference length tests. Three repeated measurements of each position are required for IFM short reference length tests.

6.4.1 Reference Length Requirements. The expanded test value uncertainty ($k=2$) of a traceable reference length (see [Mandatory Appendix I](#)) used in a ranging test should not exceed one-half of the MPE for the measurement, i.e., $C_m \geq 2$, and the value of the measurement capability index, C_m , shall be stated on [Form 4-2](#). There are several methods of implementing the ranging test, and in each method

$$C_m = \text{MPE}(L_{\text{ref}}) / U_{k=2}(L_{\text{ref}}) \geq 2$$

Table 6.3.1-1
Two-Face System Test

(21)



Position Number	Distance, D (Approximate)	Measured Horizontal Angle to Target b , deg
1	[Note (2)]	0
2	[Note (2)]	90
3	[Note (2)]	180
4	[Note (2)]	270
5	3 m	0
6	3 m	90
7	3 m	180
8	3 m	270
9	6 m	0
10	6 m	90
11	6 m	180
12	6 m	270

NOTES:

(1) The height h should be at least 1 m.(2) Minimize D in order to maximize the vertical angular range of motion between nests a and c .

6.4 Ranging Tests

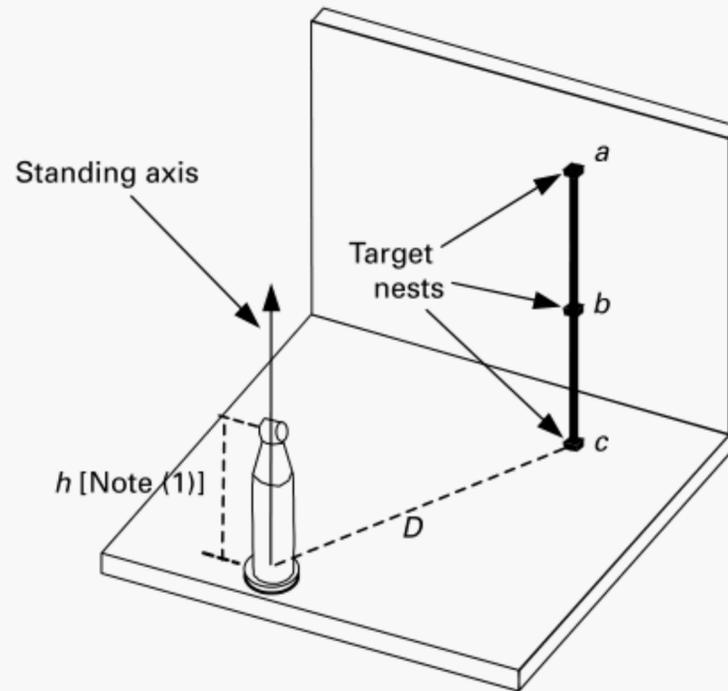
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6.4.1 Reference Length Requirements. The expanded test value uncertainty ($k=2$) of a traceable reference length (see [Mandatory Appendix I](#)) used in a ranging test should not exceed one-half of the MPE for the measurement, i.e., $C_m \geq 2$, and the value of the measurement capability index, C_m , shall be stated on [Form 4-2](#). There are several methods of implementing the ranging test, and in each method

$$C_m = \text{MPE}(L_{\text{ref}}) / U_{k=2}(L_{\text{ref}}) \geq 2$$

Table 6.3.1-1
Two-Face System Test

(21)



Position Number	Distance, D (Approximate)	Measured Horizontal Angle to Target b , deg
1	[Note (2)]	0
2	[Note (2)]	90
3	[Note (2)]	180
4	[Note (2)]	270
5	3 m	0
6	3 m	90
7	3 m	180
8	3 m	270
9	6 m	0
10	6 m	90
11	6 m	180
12	6 m	270

NOTES:

(1) The height h should be at least 1 m.(2) Minimize D in order to maximize the vertical angular range of motion between nests a and c .

6.4 Ranging Tests

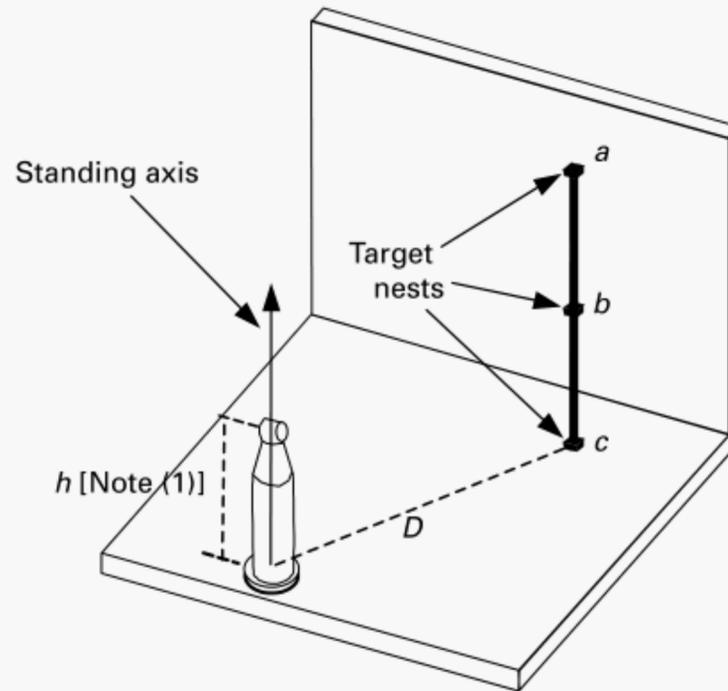
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$$C_m = \text{MPE}(L_{\text{ref}}) / U_{k=2}(L_{\text{ref}}) \geq 2$$

Table 6.3.1-1
Two-Face System Test

(21)



Position Number	Distance, D (Approximate)	Measured Horizontal Angle to Target b , deg
1	[Note (2)]	0
2	[Note (2)]	90
3	[Note (2)]	180
4	[Note (2)]	270
5	3 m	0
6	3 m	90
7	3 m	180
8	3 m	270
9	6 m	0
10	6 m	90
11	6 m	180
12	6 m	270

NOTES:

(1) The height h should be at least 1 m.(2) Minimize D in order to maximize the vertical angular range of motion between nests a and c .

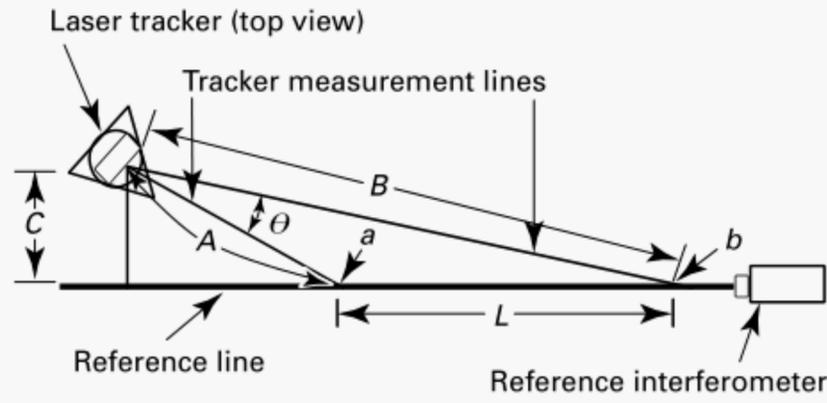
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6.4.1 Reference Length Requirements. The expanded test value uncertainty ($k=2$) of a traceable reference length (see [Mandatory Appendix I](#)) used in a ranging test should not exceed one-half of the MPE for the measurement, i.e., $C_m \geq 2$, and the value of the measurement capability index, C_m , shall be stated on [Form 4-2](#). There are several methods of implementing the ranging test, and in each method

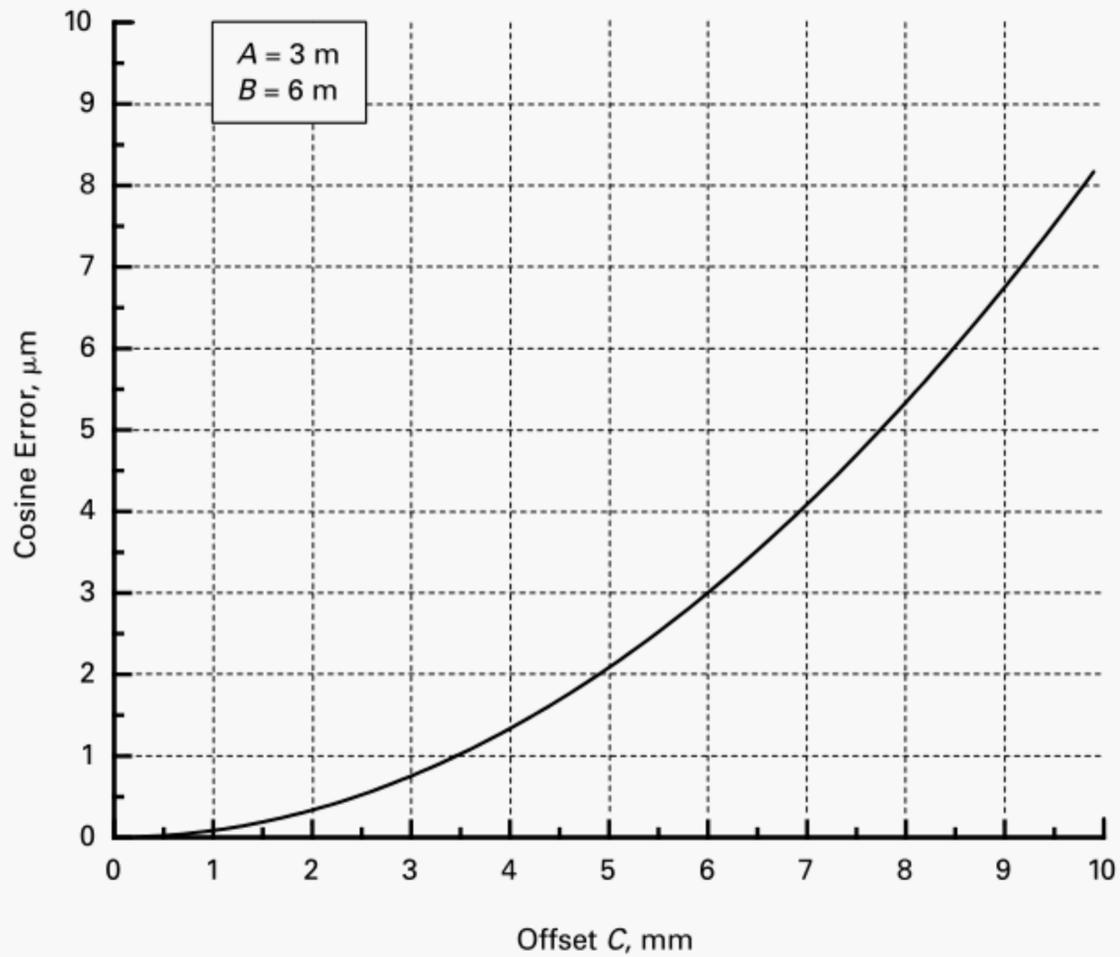
$$C_m = \text{MPE}(L_{\text{ref}}) / U_{k=2}(L_{\text{ref}}) \geq 2$$

Figure 6.4.4.1-1
Laser Tracker and Reference Interferometer Alignment



GENERAL NOTE: Endpoints of reference length are points a and b .

Figure 6.4.4.1-2
Cosine Error Versus Offset C From Reference Line



GENERAL NOTE: In this example, $A = 3 \text{ m}$ and $B = 6 \text{ m}$ (see [Figure 6.4.4.1-1](#)).

(21) 7 ANALYSIS OF PERFORMANCE EVALUATION TESTS**7.1 Evaluation of Length Measurement System Tests of [Para. 6.2](#)**

The length measurement system tests are evaluated by calculating the difference between the measured length and the reference length using [eq. \(5\)](#).

$$\delta = L_m - L_{\text{ref}} \quad (5)$$

where

L_m = length measured by the laser tracker

L_{ref} = reference length

There are three values (δ_1 , δ_2 , and δ_3) for each test position corresponding to the three repeated measurements. The test of conformance for each measured point-to-point length error requires comparing the largest value, $\delta_{\text{max}} = \max(\delta_1, \delta_2, \delta_3)$ with the tolerance limit. MPE is defined as the maximum of δ_{max} and $-\delta_{\text{min}}$. MPE is the maximum of δ_{max} and $-\delta_{\text{min}}$.

Figure 7.1-1
Form 4-2 With Example Default Method Data

(21)

Form 4-2 Manufacturer's Performance Specifications and Test Results

Test (Positions)	IFM Specifications and Test Results			ADM Specifications and Test Results		
	MPE _{IFM}	δ_{\max} or Δ_{\max} [Note (1)]	Pass	MPE _{ADM}	δ_{\max} or Δ_{\max} [Note (1)]	Pass
Horizontal (1)	30	3.5	Y	35	10.8	Y
Horizontal (2, 3, 4, 5)	40	38.1	Y	43	60.2	N
Horizontal (6, 7, 8, 9)	90	90.0	Y	91	55.1	Y
Vertical (1, 2, 3, 4)	40	25.4	Y	43	10.2	Y
Vertical (5, 6, 7, 8)	90	90.6	N	91	66.1	Y
Right Diagonal (1, 2, 3, 4)	40	35.7	Y	43	36.2	Y
Right Diagonal (5, 6, 7, 8)	90	80.6	Y	91	85.3	Y
Left Diagonal (1, 2, 3, 4)	40	25.2	Y	43	26.2	Y
Left Diagonal (5, 6, 7, 8)	90	80.6	Y	91	78.2	Y
User Selected (1)	50	43.2	Y	53	20.2	Y
User Selected (2)	15	10.0	Y	18	8.3	Y
Two Face (1, 2, 3, 4)	40	2.1 [Note (2)]	Y		[Note (2)]	
Two Face (5, 6, 7, 8)	50	33.8 [Note (2)]	Y		[Note (2)]	
Two Face (9, 10, 11, 12)	90	5.3 [Note (2)]	Y		[Note (2)]	
IFM Ranging Ref L (1) = 9 m	20	16.0 [Note (3)]	Y			
IFM Ranging Ref L (2) = 18 m	40	31.0 [Note (3)]	Y			
IFM Ranging Ref L (3) = 27 m	60	48.0 [Note (3)]	Y			
IFM Ranging Ref L (4) = 36 m	80	61.0 [Note (3)]	Y			
ADM Ranging Ref L (1) = 9 m				25	13.5	Y
ADM Ranging Ref L (2) = 18 m				50	42.2	Y
ADM Ranging Ref L (3) = 27 m				75	54.0	Y
ADM Ranging Ref L (4) = 36 m				100	95.3	Y
ADM Ranging Ref L User (1) = 22 m				23	20.1	Y
ADM Ranging Ref L User (2) = 30 m				25	23.1	Y
Formula for calculating the MPE or attach MPE specification sheet [Note (4)]	See attached specifications.			See attached specifications.		

Test Performed by: Jones Date: 3/18/2021 Instrument Serial Number: 1234
 C_m for IFM System Tests: 5.2 ; C_m for IFM Ranging Tests: 2.5 if $1 \leq C_m < 2$ Check "Low_ C_m "
 C_m for ADM System Tests: 6 ; C_m for ADM Ranging Tests: 2.1 if $1 \leq C_m < 2$ Check "Low_ C_m "
 Final Test Results (Pass/Fail): Fail

GENERAL NOTES:

- All units are in micrometers (μm).
- The IFM columns must contain specifications and results for laser trackers with IFM only, the ADM columns must contain specifications and results for instruments with ADM only, and both pairs of columns must contain specifications and results for instruments with both an IFM and an ADM.
- If an ADM result is used in place of an IFM result, the value should be placed in parentheses.

NOTES:

- δ for length system results, Δ for two-face results; see paras. 7.1 and 7.2.
- Two-face tests may be performed with either an IFM or an ADM.
- These results can be results from long reference lengths, or computed from short reference lengths (see para. 7.3.1), or computed from the laser interferometer calibration certificate (see para. 7.3.1).
- The manufacturer may specify separate MPE formulas for the system tests, ranging tests, and two-face tests.

Figure 7.1-1
Form 4-2 With Example Default Method Data

(21)

Form 4-2 Manufacturer's Performance Specifications and Test Results

Test (Positions)	IFM Specifications and Test Results			ADM Specifications and Test Results		
	MPE _{IFM}	δ_{\max} or Δ_{\max} [Note (1)]	Pass	MPE _{ADM}	δ_{\max} or Δ_{\max} [Note (1)]	Pass
Horizontal (1)	30	3.5	Y	35	10.8	Y
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Two Face (1, 2, 3, 4)	40	2.1 [Note (2)]	Y		[Note (2)]	
Two Face (5, 6, 7, 8)	50	33.8 [Note (2)]	Y		[Note (2)]	
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 C_m for ADM System Tests: 6 ; C_m for ADM Ranging Tests: 2.1 if $1 \leq C_m < 2$ Check "Low_ C_m "
 Final Test Results (Pass/Fail): Fail

GENERAL NOTES:

- (a) All units are in micrometers (μm).
- (b) The IFM columns must contain specifications and results for laser trackers with IFM only, the ADM columns must contain specifications and results for instruments with ADM only, and both pairs of columns must contain specifications and results for instruments with both an IFM and an ADM.
- (c) If an ADM result is used in place of an IFM result, the value should be placed in parentheses.

NOTES:

- (1) δ for length system results, Δ for two-face results; see paras. 7.1 and 7.2.
- (2) Two-face tests may be performed with either an IFM or an ADM.
- (3) These results can be results from long reference lengths, or computed from short reference lengths (see para. 7.3.1), or computed from the laser interferometer calibration certificate (see para. 7.3.1).
- (4) The manufacturer may specify separate MPE formulas for the system tests, ranging tests, and two-face tests.

Figure 7.1-1
Form 4-2 With Example Default Method Data

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 C_m for ADM System Tests: 6 ; C_m for ADM Ranging Tests: 2.1 if $1 \leq C_m < 2$ Check "Low_ C_m "
 Final Test Results (Pass/Fail): Fail

GENERAL NOTES:

- All units are in micrometers (μm).
- The IFM columns must contain specifications and results for laser trackers with IFM only, the ADM columns must contain specifications and results for instruments with ADM only, and both pairs of columns must contain specifications and results for instruments with both an IFM and an ADM.
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 Final Test Results (Pass/Fail): Fail

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- The manufacturer may specify separate MPE formulas for the system tests, ranging tests, and two-face tests.

MANDATORY APPENDIX I

REFERENCE LENGTH TRACEABILITY

(21)

I-1 GENERAL TRACEABILITY ISSUES

This Standard employs the interpretation of traceability described in ASME B89.7.5-2006. Two issues of traceability arise in the testing and subsequent use of laser trackers. The first issue is that if a performance evaluation is conducted on a particular laser tracker, then, in order to demonstrate that the system meets the manufacturer's specifications, the reference lengths must satisfy the traceability requirements of [section I-2](#). This provides the connection to the SI definition of the meter and allows a comparison of the measured length errors with the specified maximum permissible error (MPE) values.

One of the traceability requirements is for documentation traceability. This is a requirement to describe how the connection to the SI definition of the meter is achieved. For example, if a scale bar is employed to realize the reference length, then the documentation traceability is the calibration certificate of the scale bar to an appropriate metrological terminus. If the reference length is realized using the laser interferometer internal to the laser tracker (IFM), then this IFM must have metrological traceability to an appropriate metrological terminus (see [section I-3](#)).

The second issue of traceability is that if the laser tracker is to be used for subsequent point-to-point length measurements (e.g., by a user in a factory), then the requirements of ASME B89.7.5 must be fulfilled for the measurements to be considered traceable (see [Nonmandatory Appendix A](#)).

I-2 REFERENCE LENGTH TRACEABILITY

Each reference length required in this Standard must be traceable per ASME B89.7.5. Typically, it is not necessary to document separately the traceability of each reference length on a test position by test position basis, unless a different artifact is used to generate the reference length. For example, a calibrated scale bar might be used for the reference lengths of the system tests and a laser interferometer used for the reference lengths of the ranging tests. In such a case, the traceability requirements must be met and documented for both the scale bar and the interferometer. Supplying the following information for each artifact used will satisfy the traceability requirements for the reference lengths:

(a) State the measurand (e.g., the point-to-point length between two kinematic nests on a scale bar).

NOTE: The reference length always refers to the standard temperature of 20°C. However, it may be convenient, for measurement uncertainty considerations, to perform the calibration at a temperature other than 20°C.

(b) Identify the measurement system or standard used (e.g., a scale bar, 2.3 m long, made of steel, serial number 12345).

(c) State the expanded ($k = 2$) uncertainty associated with the reference length as used at the time of measurement. Information on evaluating the uncertainty of the reference length is given in [Nonmandatory Appendix D](#).

(d) Provide an uncertainty budget describing the uncertainty components used to compute the statement of uncertainty.

(e) Provide documentation traceability (e.g., a calibration certificate) back to an appropriate terminus of the standard used for the reference length; see [section I-3](#) for an appropriate metrological terminus.

(f) Show evidence of an internal quality assurance program so that the measurement uncertainty statement for the reference length is assured. This may be a simple procedure to ensure that the reference length artifact is periodically recalibrated, that other sensors (e.g., the weather station of a reference interferometer) are periodically recalibrated, or that the artifact fixturing or other effects are in accordance with the artifact's calibration requirements or otherwise considered in the uncertainty budget.

I-3 METROLOGICAL TERMINUS

An appropriate metrological terminus for the documentation traceability is any one of the following sources (see ASME B89.7.5 for further details):

(a) calibration report¹ from a national measurement institute for the reference length (artifact or instrument) used in the testing.

(b) calibration report from a competent² laboratory fulfilling ISO 17025, section 6.5 for the reference length used in the testing.

(c) documentation describing an independent realization of the SI definition of the meter³ used to generate the reference length. This documentation will include the measurement uncertainty of the calibration and evidence that the stated uncertainty is achievable (e.g., evidence of participation in a round robin or comparison against another independently calibrated length standard).

¹ For some instruments, accuracy is often specified by grade or class. A document identifying compliance to a metrological grade or class is equivalent to a calibration report.

² A de facto means of demonstrating competence is through laboratory accreditation.

³ In this Standard, an independent realization of the SI definition of the meter is considered a reproducible physical phenomenon that has its metrological characteristic (and reproducibility) measured and documented by a national measurement institute. Hence, reproduction of this phenomenon represents an unbroken chain of information, back to the SI unit of length; such a realization is sometimes referred to as a quantum-based standard.

NONMANDATORY APPENDIX A

TRACEABILITY OF SUBSEQUENT MEASUREMENTS

(21)

A-1 INTRODUCTION

This Appendix provides information on the traceability of subsequent measurements of the laser tracker after completion of a performance evaluation per this Standard. The example in [section A-2](#) is intended to illustrate a typical scenario. For more information on traceability, see ASME B89.7.5-2006 (R2016).

A-2 METROLOGICAL TRACEABILITY EXAMPLE

A user has a laser tracker that has successfully passed an evaluation per this Standard, i.e., all measured errors were no greater than the manufacturer's corresponding maximum permissible error (MPE) values. The user wishes to perform a series of point-to-point measurements on long aluminum structures. The laser tracker is equipped with a workpiece temperature sensor that is mounted to the workpiece. The measurements are performed in a factory environment that varies from 20°C to 30°C.

Since there are many workpieces of various lengths to measure, the user will develop a single document that will address all the anticipated measurements; the document will be kept on file in case measurement traceability must be demonstrated. This document should include the following:

(a) identification of the measurand (e.g., the point-to-point length between two points on an aluminum workpiece measured on a shop floor at a temperature between 20°C and 30°C).

NOTE: Workpiece dimensions always refer to 20°C, hence the workpiece temperature sensor measures the temperature in order to correct for thermal expansion.

(b) identification of the measurement system or standard used (e.g., laser tracker #789).

(c) a statement of the expanded ($k = 2$) uncertainty associated with the result of the measurement [e.g., $U = 11.6 \mu\text{m} + 29.0L \mu\text{m}$, where L is in meters (the statement can be in any form, e.g., a table, a formula, produced by software)].

(d) an uncertainty budget describing the uncertainty components used to compute the statement of uncertainty. In this example, the uncertainty components would include the laser tracker error as quantified by its MPE, the uncertainty in the temperature measurement, and the uncertainty in the coefficient of thermal expansion; other effects might include uncertainty components due to spherically mounted retroreflector (SMR) errors (see [Nonmandatory Appendix B](#)).

EXAMPLE: The manufacturer of a laser tracker states that the largest point-to-point length error, i.e., the MPE (regardless of direction) is $10 \mu\text{m} \pm 10L \mu\text{m}$, where L is the nominal length in meters. Suppose that the temperature is measured with a maximum error of $\pm 0.5^\circ\text{C}$, the coefficient of thermal expansion (CTE) is $(22 \pm 2) \times 10^{-6}^\circ\text{C}^{-1}$, and other uncertainty components are negligible.

If uniform probability distributions are assigned to all input quantities (except input measurements), then the expanded uncertainty

Table A-2-1
Example Uncertainty Budget

(21)

Input Quantity	Standard Uncertainty
Laser tracker	$(10 \mu\text{m} + 10L \mu\text{m}) \times 0.58 = 5.8 \mu\text{m} + 5.8L \mu\text{m}$
Temperature	$0.5^\circ\text{C} \times (22 \frac{\mu\text{m}}{\text{m}^\circ\text{C}}) \times L \times 0.58 = 0 \mu\text{m} + 6.4L \mu\text{m}$
CTE	$(2 \frac{\mu\text{m}}{\text{m}^\circ\text{C}}) \times L \times 10^\circ\text{C} \times 0.58 = 0 \mu\text{m} + 11.6L \mu\text{m}$
Combined standard uncertainty	$5.8 \mu\text{m} + 14.5L \mu\text{m}$
Expanded ($k = 2$) uncertainty	$11.6 \mu\text{m} + 29.0L \mu\text{m}$

GENERAL NOTE: L is the numerical value of length in meters.

NONMANDATORY APPENDIX B

SPHERICALLY MOUNTED RETROREFLECTOR (SMR) TESTS

B-1 INTRODUCTION

(21)

Three types of laser tracker measurement errors are attributable to spherically mounted retroreflectors (SMRs) that are cube-corner retroreflectors constructed of three mirrors. SMRs containing glass cube corners (rather than three mirrors) are subject to these same errors as well as additional errors, due to refraction, that are not discussed here. The three types of errors are

- (a) vertex-centering error (radial or lateral)
- (b) dihedral-angle error
- (c) polarization error

The degradation in laser tracker measurements resulting from the vertex-centering error is solely dependent on the properties of the SMR and can be evaluated with the methods described in [section B-2](#). The other two errors (dihedral-angle error and polarization error) depend not only on the properties of the SMR but also on the properties of the laser tracker. Dihedral-angle errors are discussed in [section B-3](#); polarization errors are discussed in [section B-4](#).

B-2 DETERMINING CENTERING ERROR OF VERTEX OF SMR

B-2.1 Lateral Centering

(21)

As shown in [Figure B-2.1-1](#), the operator places the SMR in a nest on a microscope stand and uses a light source to illuminate the frame of the microscope. The operator turns the focus adjustment to view a speck of dust (or other small object) sitting on the microscope frame, then rotates the SMR within the nest and notes the diameter of the runout pattern. The lateral error in the centering of the SMR vertex is found by dividing the observed runout diameter by four.

To understand this result, consider [Figure B-2.1-1](#). The lateral offset error, b , is equal to the distance from the axis of rotation to the axis of the vertex. As the SMR is rotated within the nest, the vertex undergoes a mechanical runout of $2b$. Because the tip of the virtual object is found by projecting the tip of the object through the vertex, the virtual speck moves twice as far as the vertex. In other words, the microscope sees an optical runout (determined by the movement of the virtual object) of $4b$.

This procedure requires a separate calibration of the microscope graticule. The calibration procedure may consist of placing a calibrated reference scale on the base of the microscope. The divisions on the reference scale are then compared directly to the divisions of the graticule.

B-2.2 Radial Centering

(21)

As shown in [Figure B-2.2-1](#), a reference ball of diameter d is gently placed on the cube-corner retroreflector of the SMR. A gage with an uncertainty ($k = 1$) of less than $2.5 \mu\text{m}$ [e.g., a linear variable differential transformer (LVDT)] is used to measure the combined height, h , of the SMR and the reference ball. This gage is also used to measure the diameter, D , of the SMR. The error in the depth of the SMR vertex with respect to the center of the sphere is

$$h - \frac{D}{2} - \frac{d(1 + \sqrt{3})}{2} = h - 0.5D - 1.3660d \quad (\text{B-1})$$

The following is an explanation of [eq. \(B-1\)](#): in an ideal SMR, the distance from the bottom of the SMR to the vertex is $D/2$. The sides of the reference sphere touch the cube-corner mirrors a distance of $d/2$ from the vertex, so the distance from the vertex to the center of the reference sphere is $(d\sqrt{3}/2)$. The distance from the center of the reference ball to the top of the reference ball is $d/2$. The height of a reference ball within an ideal SMR is then the sum of these three quantities or $D/2 + d(1 + \sqrt{3})/2$.

Figure B-2.1-1
Microscope Schematic for Measuring Lateral Centering Error

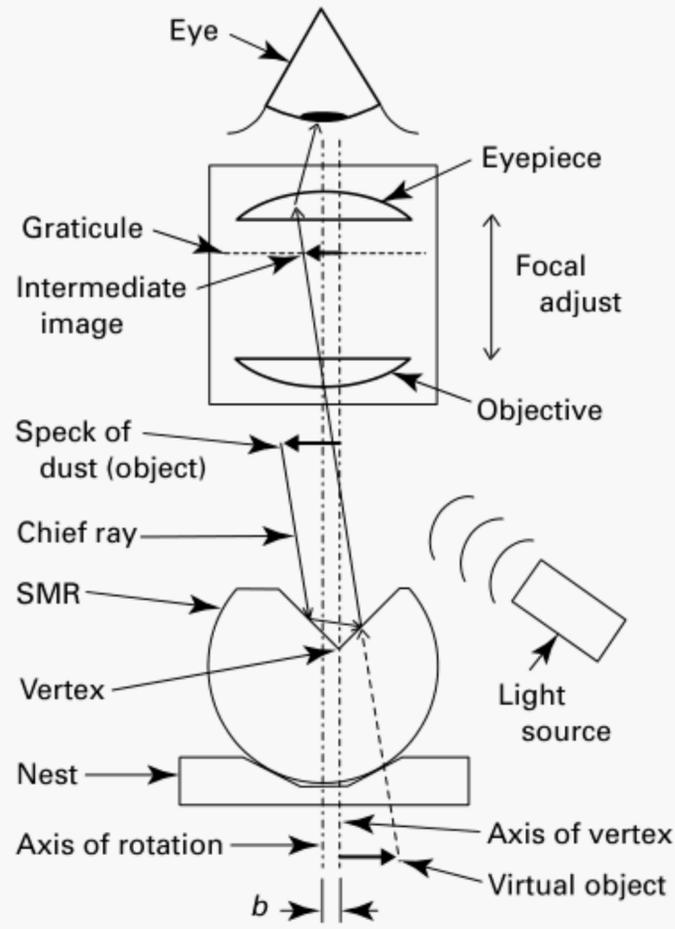
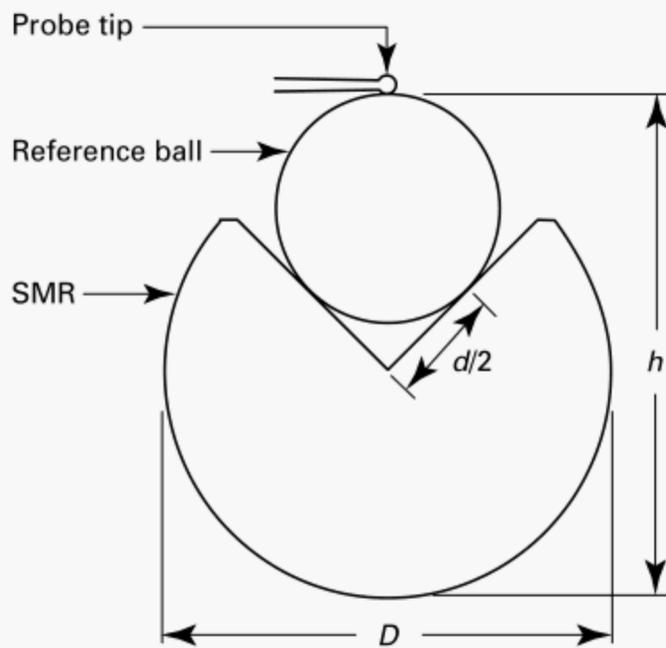


Figure B-2.2-1
Setup for Measuring Radial Centering Error



GENERAL NOTE: This figure represents a two-dimensional cross section of a three-dimensional scenario.

B-3 DIHEDRAL-ANGLE ERRORS

(21)

In an ideal cube corner, the angle between each of the three pairs of mirror faces is exactly 90 deg. In a real cube corner, these angles may differ from the ideal by a few arcseconds. This difference, called the dihedral-angle error, can degrade laser tracker performance if the SMR is used with a system that does not maintain perfect laser-beam retrace.

To understand laser-beam retrace, first consider the perfect retrace condition shown in [Figure B-3-1](#). A laser beam passes through a beam splitter inside the laser tracker, then passes out of the laser tracker and travels to the cube-corner retroreflector of the SMR. The laser beam reflects backward, exactly retracing the path of the incident laser beam. Once inside the laser tracker, some of the laser light reflects off the beam splitter and travels to a position-sensitive detector (PSD). A point on the surface of the PSD is designated as the control point. The laser tracker's servo subsystem drives the beam steering mirror subsystem so as to keep the beam centered on the control point. As long as the correct control point has been chosen, the laser beam is kept centered on the cube corner of the SMR, thereby causing the laser beam to exactly retrace itself.

If the position of the control point on the surface of the PSD is set incorrectly, as shown in [Figure B-3-2](#), the reflected laser beam will not retrace the path of the incident laser beam.

Now consider a ray of light reflected off the three mutually perpendicular surfaces of a cube-corner retroreflector, as shown in [Figure B-3-3](#). The three mirrors lie in the XY plane, the YZ plane, and the ZX plane, respectively. The ray first strikes the YZ plane at point 1, then the XY plane at point 2, and finally the ZX plane at point 3. The ray of light emerges from point 3 parallel to the ray incident on point 1.

[Figure B-3-4](#) shows these same three points as viewed in a plane perpendicular to the axis of symmetry of the cube corner. Note that if the ray reverses its direction and begins at point 3, it will travel to point 2 and then point 1. Also note that the origin (vertex) of the cube corner bisects the line segment connecting points 1 and 3.

The surface of the cube corner can be divided into six segments, A through F, by extending the lines of intersection of the three mirrors, as shown in [Figure B-3-5](#). For the direction of the incoming laser beam considered here, any ray striking segment B will strike segment C and then segment E. The reverse is also true; any ray striking segment E will strike segment C and then segment B.

If the dihedral-angle errors are not zero, the reflected rays will not be exactly parallel to the incident rays. Suppose that the incident rays of laser light are parallel to the axis of symmetry of the cube corner in [Figure B-3-5](#). Then, as a specific example, such rays incident on segment B may bend outward (leftward) by 1 arcsecond when they emerge from segment E. In this case, rays incident on segment E bend outward (rightward) by the same angle (1 arcsecond) when they emerge from segment B.

In general, collimated laser light incident on all six segments separates into six distinct segments after reflection. Each segment travels in a slightly different direction. Opposing segments (i.e., segments A–D, B–E, and C–F) bend in equal and opposite directions. Because of this symmetry, if the incoming laser beam is centered on the vertex of the cube corner, the optical-power centroid of the reflected laser beam will coincide with the optical-power centroid of the incident laser beam. In this sense, the beam retraces its path back into the laser tracker and the perfect retrace condition of [Figure B-3-1](#) prevails.

Now suppose that the wrong control point has been chosen for the PSD. As shown in [Figure B-3-2](#), the incoming and outgoing laser beams do not coincide. For the case shown in [Figure B-3-6](#), the center of the incident laser beam is right of the vertex, and the center of the reflected laser beam is an equal distance left of the vertex. It follows that more of the optical power impinges on segment B and reflects off segment E than impinges on E and reflects off B. If the rays from E bend left by 1 arcsecond and the rays from B bend right by 1 arcsecond, then the left-bending rays will dominate. The reflected beam then strikes the PSD off the control point, causing the servo subsystem of the laser tracker to redirect the

To see the runout pattern, lock a laser tracker onto an SMR that has been placed in a kinematic nest. Rotate the SMR in the nest while watching the readings of the angular encoders. The maximum allowable dihedral angles of the cube corners are set by each laser tracker manufacturer according to the accuracy of the PSD control point and the stringency of the laser tracker specifications.

B-4 POLARIZATION EFFECTS

The manufacturer of a laser tracker should state whether the ranging subsystem using the interferometer (IFM) or absolute distance meter (ADM) within the laser tracker is sensitive to the polarization state of the laser light reflected into the laser tracker. If the laser tracker is sensitive to polarization, then the reflective properties of the SMR mirror coatings become important. Mirror coatings may comprise a reflective metal such as silver, a multilayer stack of thin dielectric films, or a reflective metal topped with a protective dielectric stack. Regardless of the type of coating, the laser light undergoes a change in polarization state as it successively reflects off the three SMR mirrors. Generally, the polarization effects are increased as the axis of symmetry of the cube corner is tilted away from the laser beam. It is important, therefore, to select SMR cube corners having polarization properties appropriate for the laser trackers with which they are used. The laser tracker manufacturer can recommend SMR manufacturers as well as tests to quantify SMR polarization performance.

Figure B-3-1
Beam Orientations That Minimize Effects of Dihedral Angle Errors

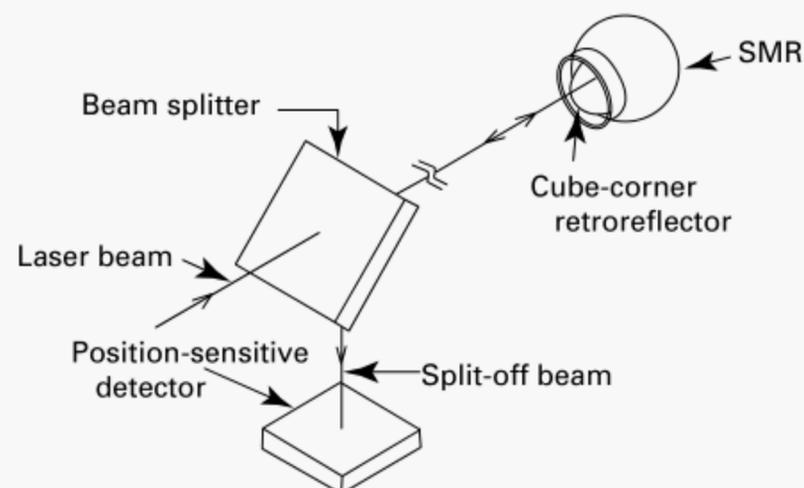


Figure B-3-2
Laser Path With Unintended Offset Between Incoming and Outgoing Beams

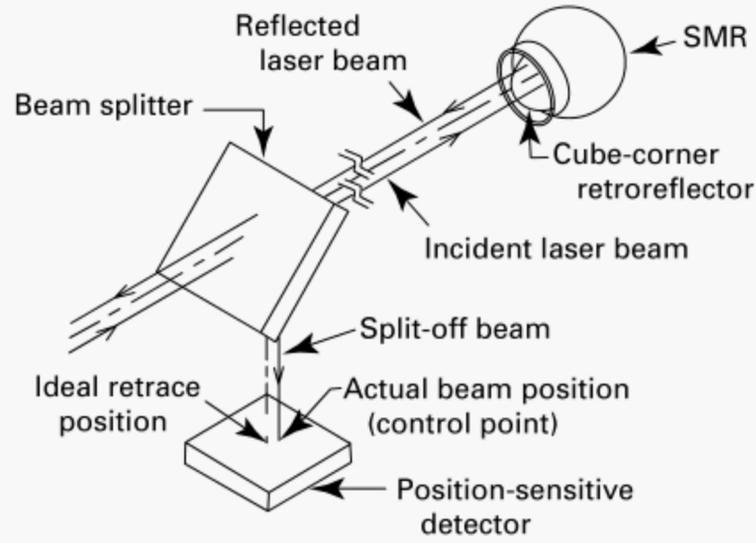
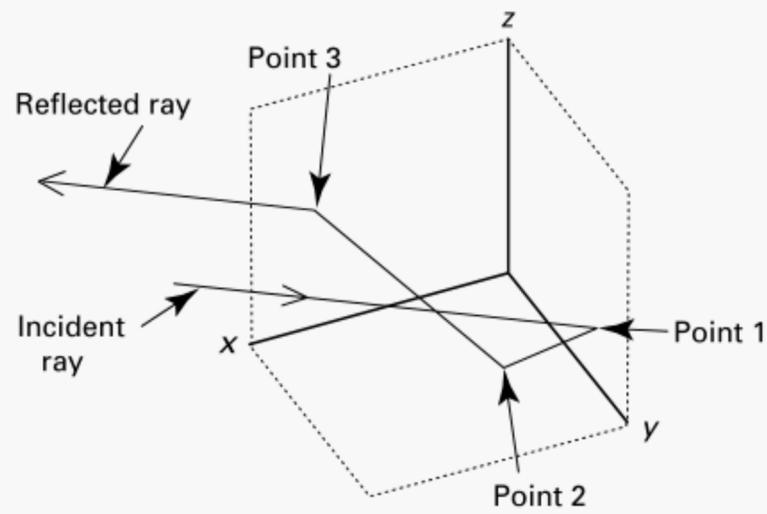


Figure B-3-3
Path of Laser Beam in Cube-Corner Retroreflector



Three Mutually Perpendicular Mirrors

Figure B-3-4
Top View of Laser Beam Path in Cube-Corner Retroreflector

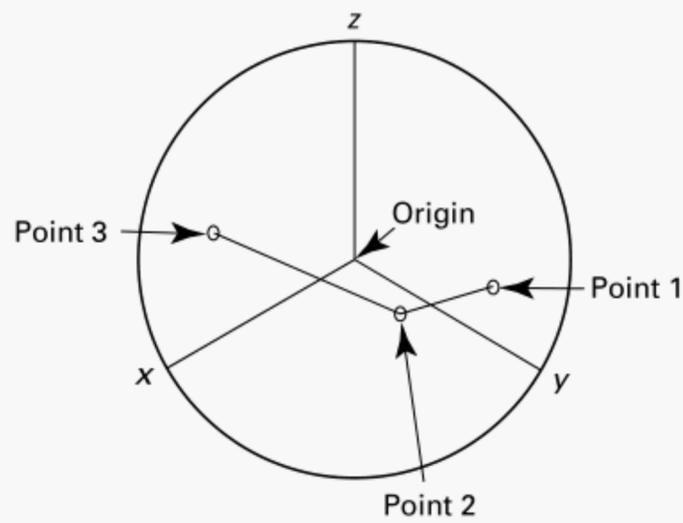


Figure B-3-5
Top View of Cube Corner With Extended Lines of Intersection

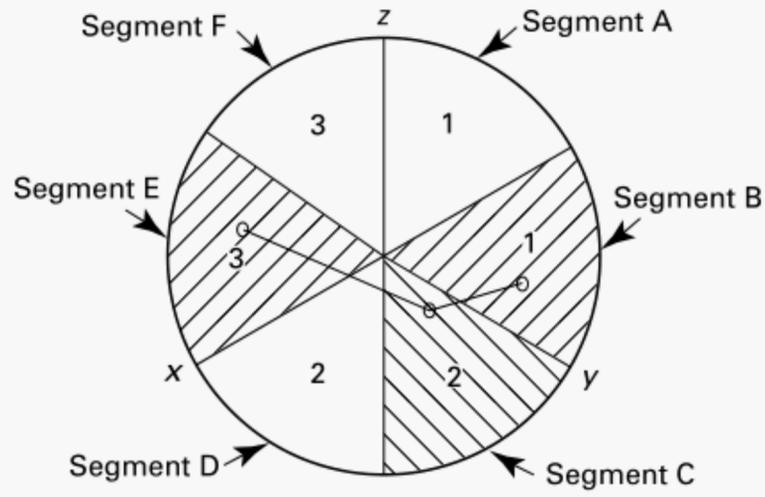


Figure B-3-6
Laser Beams Superimposed on Top View of Dihedral Prism

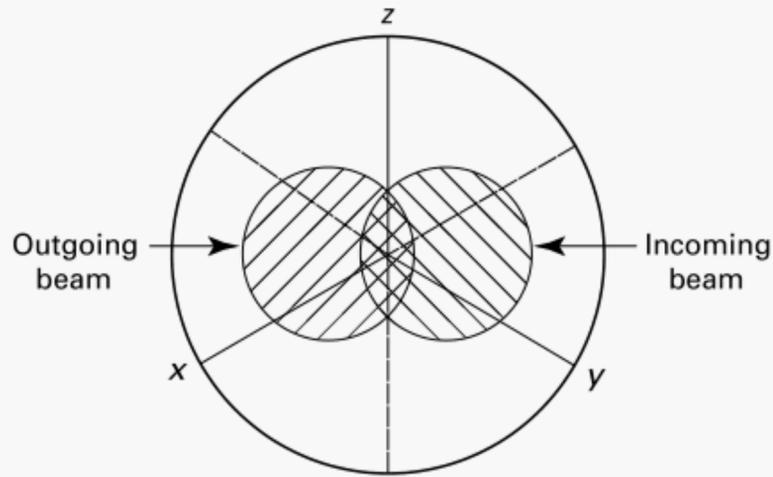


Figure B-3-7
Encoder Runout Pattern

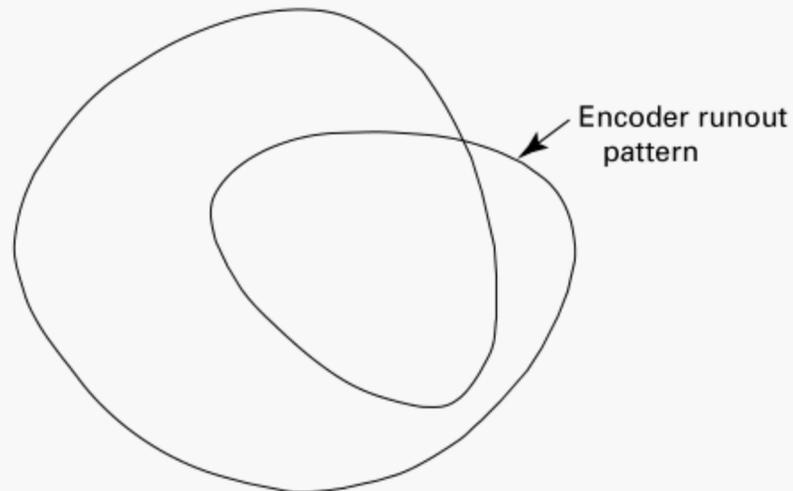


Figure B-3-5
Top View of Cube Corner With Extended Lines of Intersection

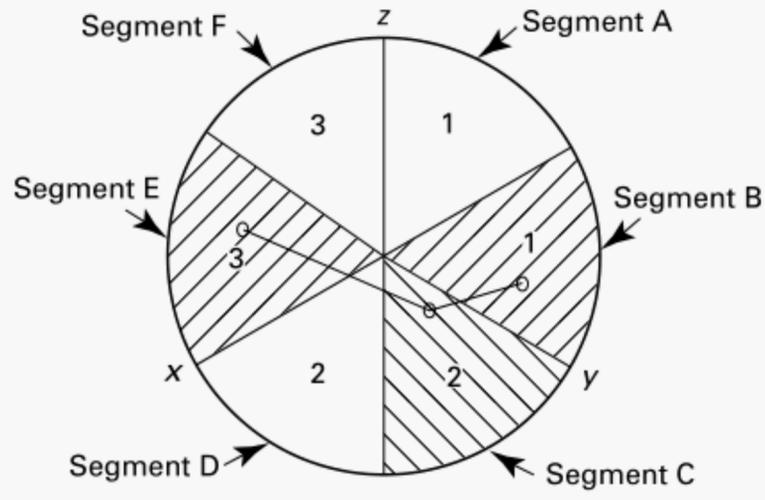


Figure B-3-6
Laser Beams Superimposed on Top View of Dihedral Prism

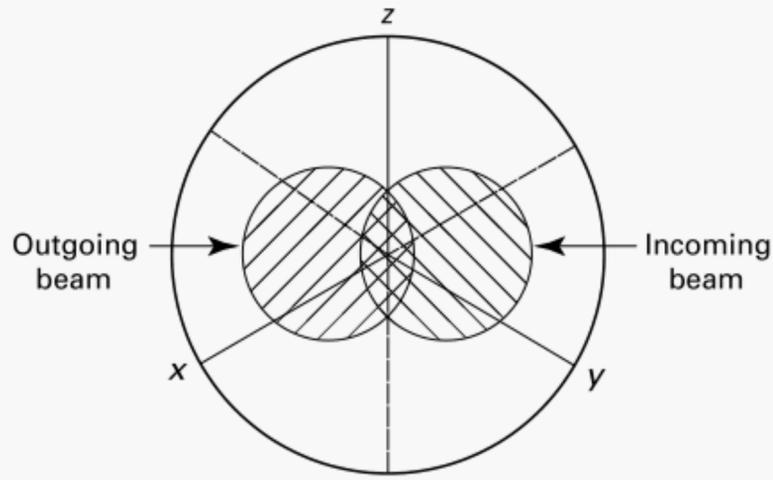
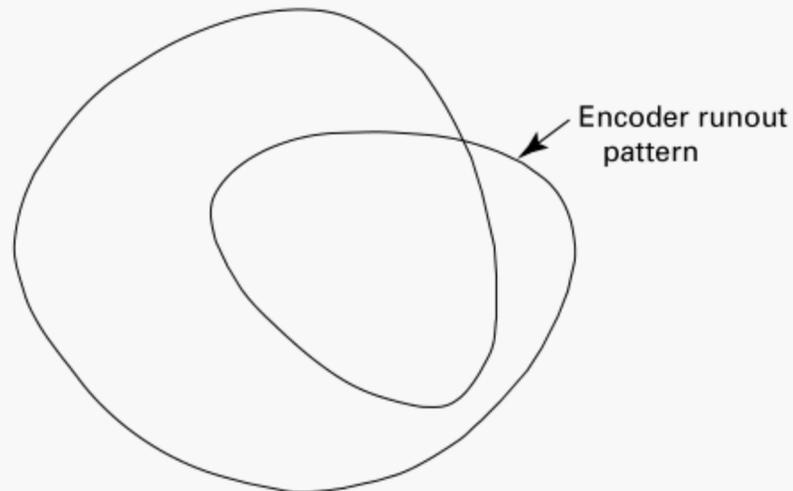


Figure B-3-7
Encoder Runout Pattern



(21) C-4 EQUATIONS FOR REFRACTIVE INDEX OF AIR

In addition to its dependence on wavelength, the refractive index of air depends primarily on air pressure, temperature, humidity, and carbon dioxide concentration. Several equations have been proposed to calculate the refractive index, given values of wavelength and environmental parameters. The equations from Ciddor² and Ciddor and Hill³ are recommended for use with this Standard. These equations are valid over a wide range of wavelengths (300 nm to 1 690 nm), temperatures (−20°C to 100°C), pressures (800 hPa to 1 200 hPa), and humidities (0% to 100%).

The National Institute of Standards and Technology (NIST) maintains a web-based tool for calculating the refractive index of air and wavelength of light in air using the Ciddor equation, given values of various input parameters.⁴ For exact values of the input parameters, the uncertainties in calculated values of the refractive index are a few parts in 10⁸, only required for the highest level of length metrology.

The Ciddor equation yields the phase refractive index, n , directly. By varying the input wavelength and noting the corresponding change in n , the dispersion, $dn/d\lambda$, can be evaluated numerically and the group refractive index can then be calculated using eq. (C-3).

The remainder of this Appendix discusses the uncertainty of displacement measurements made with a laser tracker IFM subsystem. Corresponding results for absolute distance meter (ADM) measurements can be derived using group refractive index values appropriate for the wavelength of the ADM light source.

(21) C-4.1 Simplified Equation for HeNe Laser Displacement Interferometers

Most commercial laser trackers use HeNe displacement interferometers, operating at wavelength $\lambda \approx 633$ nm, to realize their IFM ranging subsystems. For such IFMs, and for levels of uncertainty required in laser tracker performance evaluation, a simplified equation⁴ can be used to calculate the refractive index of air.

$$n = 1 + 7.86 \times 10^{-4} \frac{P}{T + 273} - 1.5 \times 10^{-11} RH(T^2 + 160) \quad (\text{C-4})$$

where

P = air pressure, kPa (101.325 kPa = 760 mmHg)

RH = relative humidity, % (0% ≤ RH ≤ 100%)

T = air temperature, °C

The expanded uncertainty of the refractive index evaluated using eq. (C-4) is $U_{k=2}(n) \approx 1.5 \times 10^{-7}$ for a perfectly homogeneous beam path and exact values of the environmental parameters. In practice, the uncertainty will always be greater than this because of sensor errors and refractive index variations (due to temperature gradients, for example; see [Nonmandatory Appendix E](#)) along the IFM beam path.

(21) C-5 REFRACTIVE INDEX UNCERTAINTY AND DISPLACEMENT MEASUREMENTS

At the levels of uncertainty required for the performance evaluation tests prescribed in this Standard, the components of uncertainty in refractive index due to the laser vacuum wavelength, relative humidity along the beam path, and carbon dioxide concentration are generally negligible. In such a case, the uncertainty of the refractive index will be dominated by components associated with possible temperature and pressure contributions.

Denoting the nominal refractive index in a displacement measurement by $n(P, T)$, the standard uncertainty is then

$$u(n) = \sqrt{c_P^2 u^2(P) + c_T^2 u^2(T)} \quad (\text{C-5})$$

where $u(P)$ and $u(T)$ are the standard uncertainties in average air pressure and temperature, respectively, along the path of the measured displacement. For standard dry air and wavelength $\lambda = 633$ nm, the sensitivity coefficients in eq. (C-5) are

$$c_T = \frac{\partial n}{\partial T} = -1.0 \times 10^{-6} \text{ } ^\circ\text{C}^{-1} \quad (\text{C-6})$$

²From Ciddor (1996).

³From Ciddor and Hill (1999).

⁴From Stone and Zimmerman, "Refractive Index of Air Calculator."

$$c_P = \frac{\partial n}{\partial P} = 2.7 \times 10^{-9} \text{Pa}^{-1} \quad (\text{C-7})$$

Consider an IFM system that measures a displacement, L_m , in an environment at temperature, T , and pressure, P , as measured by the system weather station sensors. The measured displacement is then

$$L_m = \frac{L_{\text{vac}}}{n} \quad (\text{C-8})$$

where L_{vac} is the displacement that would be measured in a vacuum and $n = n(P, T)$ is the average refractive index along the beam path. Assuming a negligible uncertainty in L_{vac} (i.e., a perfect fringe counting system and a known vacuum wavelength), the standard uncertainty of the measured displacement is

$$u(L_m) = \frac{L_m}{n} u(n) \quad (\text{C-9})$$

and since $n \approx 1$,

$$u(L_m) = L_m \sqrt{c_P^2 u^2(P) + c_T^2 u^2(T)} \quad (\text{C-10})$$

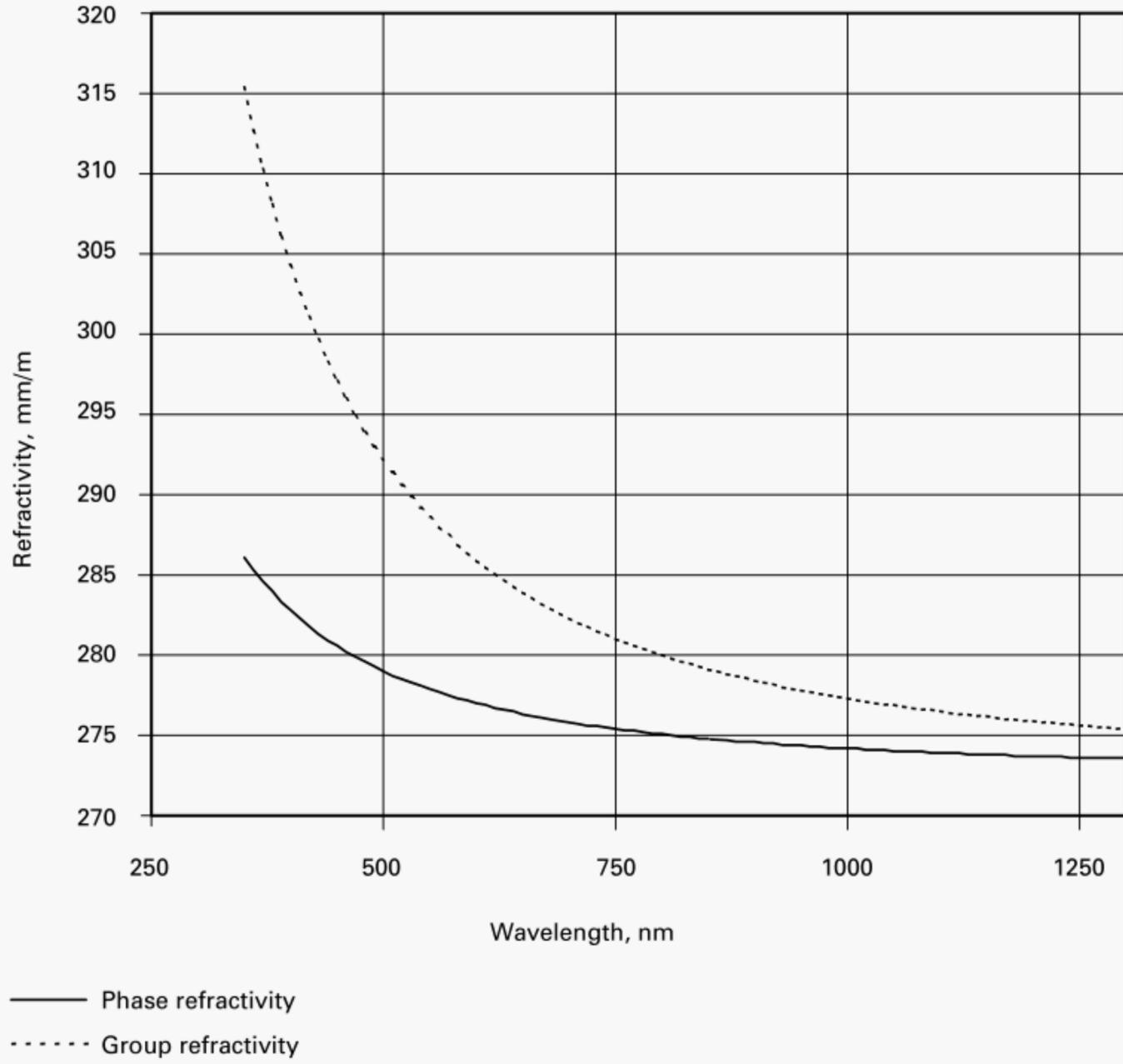
using the uncertainty given by eq. (C-5).

If one's knowledge of possible sensor errors is such that $P = P_0 \pm \Delta P$ and $T = T_0 \pm \Delta T$, where P_0 and T_0 are best estimates, then assigning uniform probability distributions to these parameters yields $u(P) = \Delta P / \sqrt{3}$ and $u(T) = \Delta T / \sqrt{3}$. Then eq. (C-10) becomes

$$u(L_m) = L_m \sqrt{c_P^2 \frac{(\Delta P)^2}{3} + c_T^2 \frac{(\Delta T)^2}{3}} \quad (\text{C-11})$$

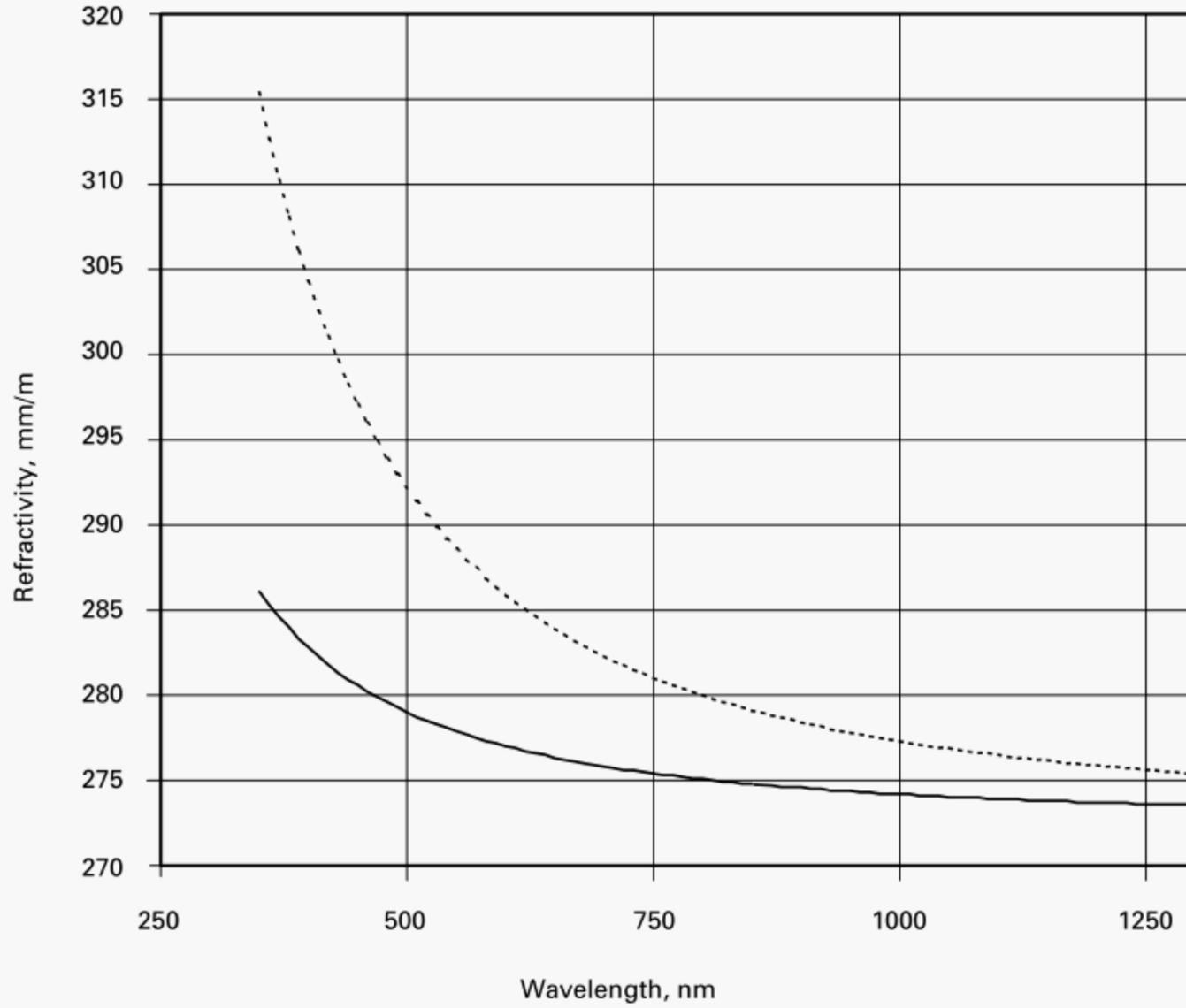
Figure C-5-1 shows the change in phase refractivity ($n - 1$) and group refractivity ($n_g - 1$), for standard dry air, versus wavelength. Standard dry air is defined by Ciddor² to be air at 15°C, 1 013.25 hPa, and 0.045% CO₂ content with 0% humidity.

Figure C-5-1
Refractivity for Standard Dry Air



GENERAL NOTE: Phase refractivity = $n - 1$ and group refractivity = $n_g - 1$.

Figure C-5-1
Refractivity for Standard Dry Air



— Phase refractivity
 - - - - - Group refractivity

GENERAL NOTE: Phase refractivity = $n - 1$ and group refractivity = $n_g - 1$.

With no correction being made to the measured length, L_m , and with the laser tracker providing the measured length digitally, the value of L_m is considered exact, and there is no uncertainty associated with it. Since $u(L_m) = 0$, and since, according to eq. (D-1), the only other term affecting the test value is L_{ref} , then

$$u(\delta) = u(L_{ref}) \quad (D-3)$$

From eq. (D-2) it then follows that the 4:1 decision rule requirement is met when the uncertainty in the value of the reference length is small enough so that

$$C_m = \frac{MPE}{2u(L_{ref})} \geq 4 \quad (D-4)$$

Different ways of realizing the reference length, along with influence factors that contribute to the uncertainty $u(L_{ref})$, are discussed in sections D-3 through D-6.

D-3 REFERENCE LENGTH REALIZED USING A CALIBRATED SCALE BAR

In this method of realizing a reference length, a scale bar with kinematic SMR nests, which has been independently calibrated (i.e., not calibrated by the tracker under test), is used.

D-3.1 Uncertainty in the Calibration

Consider a scale bar that has been calibrated at a temperature, T_0 . The reference length realized at temperature T_0 is L_{ref}^0 , with a standard uncertainty of $u_{cal}(L_{ref}^0)$. This calibration uncertainty is evaluated based on the details of the calibration process and includes a component due to uncertainty in the nominal temperature, T_0 .

D-3.2 Temperature Dependence of Reference Length

If the scale bar is used to realize a reference length at a different temperature, $T \neq T_0$, then a correction must be applied for thermal expansion or contraction. The reference length L_{ref} at temperature T is given by the correction

$$L_{ref} = L_{ref}^0 [1 + \alpha(T - T_0)] \quad (D-5)$$

where α is the coefficient of thermal expansion (CTE) of the scale bar.¹

Because the temperature, T , and the CTE, α , are not known exactly, the correction cannot be performed exactly. The standard uncertainty arising from uncertainty in the CTE, α , is

$$u_{CTE}(L_{ref}) = L_{ref}^0 |T - T_0| u(\alpha) \quad (D-6)$$

and the standard uncertainty arising from uncertainty in the temperature, T , is

$$u_T(L_{ref}) = \alpha(L_{ref}^0) u(T) \quad (D-7)$$

Equations (D-5) through (D-7) provide the necessary formulas for calculating the corrected reference length and the associated standard uncertainties when using the scale bar at a temperature other than T_0 .

D-3.3 Effect of Drift

While para. D-3.2 addresses the uncertainty in the length of the scale bar due to temperature effects, other factors (e.g., humidity) may also contribute to drift in the length of the scale bar, especially if it is made of carbon fiber. The standard uncertainty, $u_{drift}(L_{ref})$, may be determined experimentally.

D-3.4 Orientation of the Scale Bar

The length of the scale bar is likely to change due to gravitational effects for different orientations of the bar. If the length of the scale bar is calibrated for each orientation, and that value is used in the determination of the error in the measured length, the contribution of this term is negligible. However, if the scale bar is only calibrated in one orientation, and that value is used as the reference length for all orientations, the contribution from this error source must be included in the

¹ Strictly speaking, the CTE is a function of temperature. Following common engineering practice, the quantity α in eq. (D-5) is the average value of the expansion coefficient over the temperature range $T - T_0$, and it is assumed that $\alpha(T - T_0) \ll 1$ for any temperatures encountered during laser tracker performance evaluation testing.

test value uncertainty. The standard uncertainty, $u_{or}(L_{ref})$, may be determined experimentally or from modeling the effect of gravity on the length of the scale bar. The subscript “or” indicates that this term arises from the orientation of the scale bar.

D-3.5 Effect of Mounting

The length of the scale bar is dependent on the location of its support and mounting mechanism. If the scale bar is calibrated on the same support and mounting mechanism that will later be used, the scale bar’s length does not change because of the mounting mechanism between calibration and use, and therefore there is no uncertainty in the scale bar’s length due to mounting. However, if the scale bar is removed from its mount after calibration and refixed prior to use, the change in the length of the scale bar has to be accounted for in the calculation of the uncertainty. The standard uncertainty, $u_{fixt}(L_{ref})$, may be determined experimentally or from modeling the effect of fixturing on length of the scale bar. Details on effect of mounting can be found in “A Model for Geometry-Dependent Errors in Length Artifacts.”²

D-3.6 Spherically Mounted Retroreflector (SMR)

As described in para 6.1, it is generally not permitted to employ special equipment, such as high-accuracy SMRs that do not convey with the laser tracker, during testing. As a result, the performance specifications provided by the manufacturer include any errors resulting from the eccentricity between the optical and mechanical centering of the SMRs, and this error source is therefore not accounted for in the test value uncertainty. However, if SMRs are provided by the user based on mutual agreement between the user and the manufacturer, SMR errors are accounted for as follows:

(a) If it is the responsibility of the user to provide the SMR for the testing procedure, and the manufacturer’s specifications are valid over certain defined tolerances for optical and mechanical centering errors of the SMR, then, if the centering errors are smaller than the stated tolerances, there is no additional contribution to the test value uncertainty.

(b) If it is the responsibility of the user to provide the SMR for the testing procedure, but the manufacturer’s specifications are valid only for high-accuracy or perfect SMRs, then the errors resulting from the eccentricity between the optical and mechanical centering of a lower-accuracy SMR should be accounted for in the test value uncertainty. The standard uncertainty, $u_{SMR}(L_{ref})$, may be determined experimentally or from specifications provided by the manufacturer of the SMR.

D-3.7 Combined Standard Uncertainty

The combined standard uncertainty in the reference length is calculated as the root sum of squares of the terms described in paras. D-3.1 through D-3.6. Thus

$$u(L_{ref}) = \sqrt{u_{cal}^2(L_{ref}^0) + u_T^2(L_{ref}) + u_{CTE}^2(L_{ref}) + u_{drift}^2(L_{ref}) + u_{or}^2(L_{ref}) + u_{fixt}^2(L_{ref}) + u_{SMR}^2(L_{ref})} \quad (D-8)$$

This set of uncertainty sources is sufficient for most reference lengths. Should there be other factors that cause a difference in the reference length between when calibrated and when presented to the laser tracker for testing, these additional factors would also need to be considered.

D-3.8 Example

An aircraft manufacturer wishes to use a laser tracker to measure large aluminum parts. The performance of the laser tracker is evaluated using a set of point-to-point length measurements as described in para. 6.2.

The reference length for the performance evaluation tests is realized using an Invar scale bar of nominal length 3 m and a CTE of $(2.0 \pm 0.5) \times 10^{-6} \text{ } ^\circ\text{C}^{-1}$. The scale bar has been calibrated in a temperature-controlled metrology laboratory.

The calibration certificate supplied by the laboratory states the calibrated reference length at temperature $T_0 = 20^\circ\text{C}$ as $L_{ref}^0 = 3.010125 \text{ m}$ with a $k = 2$ expanded uncertainty of $U = 10 \text{ } \mu\text{m}$. The uncertainty in the calibrated length, L_{ref}^0 , already includes a component due to uncertainty in the nominal 20°C calibration temperature.

When the performance evaluation test is performed on the shop floor, the average temperature of the scale bar is estimated to be $25^\circ\text{C} \pm 0.5^\circ\text{C}$ based on a single temperature measurement using a thermocouple attached to the center of the bar. The maximum distance from the laser tracker to the scale bar during this test is approximately 5 m. The shop floor environment conforms to the rated operating conditions of the laser tracker. Other sources of uncertainty discussed in paras. D.3.3 through D.3.6 are considered to be negligible in this example.

²D. Sawyer et al., “A Model for Geometry-Dependent Errors in Length Artifacts,” Journal of Research of the National Institute of Standards and Technology, 117 (2012).

The manufacturer's performance specification for the laser tracker states an MPE of 60 μm when measuring a point-to-point nominal length of 3 m at a range of 5 m. The result of the test is a measured length of $L_m = 3.010190$ m.

Question: Does the laser tracker meet its MPE performance specification for this point-to-point length measurement?

Solution: Before an acceptance decision can be made, the measurement capability index, C_m , must be evaluated in order to ensure that it satisfies the 4:1 simple acceptance requirement that $C_m = \text{MPE}/[2u(L_{\text{ref}})] \geq 4$, with $\text{MPE} = 60 \mu\text{m}$.

The required uncertainty components are evaluated as follows:

(a) The expanded uncertainty in the calibration certificate is given as $U_{k=2} = 2u(L_{\text{ref}}^0) = 10 \mu\text{m}$. Thus, the standard uncertainty, $u_{\text{cal}}(L_{\text{ref}}^0)$, is given by $u_{\text{cal}}(L_{\text{ref}}^0) = 5 \mu\text{m}$.

(b) The uncertainty of the scale bar temperature, $u(T)$, during the test assumes a uniform distribution of width $\pm 0.5^\circ\text{C}$ about the best estimate of 25°C . It is known mathematically that the standard deviation of an interval of uniform distribution is half the width of the interval divided by $\sqrt{3}$. Thus

$$u(T) = (0.5^\circ\text{C})/\sqrt{3}$$

The uncertainty component due to temperature uncertainty [from eq. (D-7)] is then

$$\begin{aligned} u_T(L_{\text{ref}}) &= \alpha(L_{\text{ref}}^0)u(T) \\ &= (2.0)(3.0)\left(\frac{0.5}{\sqrt{3}}\right)\mu\text{m} \\ &\approx 1.7 \mu\text{m} \end{aligned}$$

(c) The uncertainty $u(\alpha)$ in the coefficient of thermal expansion, assuming a uniform distribution of width $\pm 0.5 \times 10^{-6}^\circ\text{C}^{-1}$ about the estimate of $2 \times 10^{-6}^\circ\text{C}^{-1}$, is

$$u(\alpha) = (0.5 \times 10^{-6}^\circ\text{C}^{-1})/\sqrt{3}$$

The uncertainty component due to CTE uncertainty [from eq. D-6] is then

$$\begin{aligned} u_{\text{CTE}}(L_{\text{ref}}) &= L_{\text{ref}}^0 |T - T_0| u(\alpha) \\ &= (3.0)(5.0)\frac{0.5}{\sqrt{3}} \mu\text{m} \\ &\approx 4.3 \mu\text{m} \end{aligned}$$

Then, from using eq. (D-8) with negligible terms eliminated, we have

$$\begin{aligned} u(L_{\text{ref}}) &= \sqrt{u_{\text{cal}}^2(L_{\text{ref}}^0) + u_T^2(L_{\text{ref}}) + u_{\text{CTE}}^2(L_{\text{ref}})} \\ &= \sqrt{(5.0)^2 + (1.7)^2 + (4.3)^2} \\ &\approx 6.8 \mu\text{m} \end{aligned}$$

Thus the measurement capability index is

$$C_m = \frac{60}{2 \times 6.8} \approx 4.4$$

which satisfies the requirement of eq. (D-4) for a simple 4:1 acceptance decision rule.

The reference length, L_{ref} , in the shop floor environment is calculated using eq. (D-5), with $L_{\text{ref}}^0 = 3.010125$ m, $\alpha = 2 \times 10^{-6}^\circ\text{C}^{-1}$, and $T - T_0 = 5^\circ\text{C}$.

$$\begin{aligned} L_{\text{ref}} &= 3.010125[1 + (2 \times 10^{-6}) \times 5] \\ &= 3.010155 \text{ m} \end{aligned}$$

From eq. (D-1), the observed error is

$$\begin{aligned}\delta &= L_m - L_{\text{ref}} \\ &= (3.010190 - 3.010155) \\ &= 35 \mu\text{m}\end{aligned}$$

Since $|\delta|$ is less than the stated MPE of $60 \mu\text{m}$, and since $C_m > 4$, the decision rule outcome is “acceptance” that the laser tracker meets the manufacturer’s MPE specification for this test.

Note that in this example the thermally related uncertainty sources were significant. An in situ calibration of the scale bar at the temperature of the test environment could significantly reduce these uncertainty sources, which could be helpful for meeting the 4:1 requirement when testing laser trackers that have smaller MPEs.

D-4 REFERENCE LENGTH REALIZED USING TARGET NESTS CALIBRATED USING AN IFM

In this method of realizing a reference length, kinematic nests for SMRs are mounted on each of two stable structures, such as commercially available tripod stands used for mounting optical tooling. The kinematic nests may also be near the ends of a scale bar. The distance between the kinematic nests is measured using a displacement interferometer. The interferometer laser beam is aligned parallel to the line joining the two kinematic nests, and the interferometer measures the displacement of an SMR as it is moved from one nest to the other. This measured displacement is the reference length realized by the two SMR positions.

For laser trackers that include an IFM that has passed one of the test procedures of para. 6.4.2, the IFM may be used to establish the reference length. The laser tracker should be aligned relative to the two nests so that the distance between them can be measured using the IFM only (i.e., a purely radial measurement).

In this case, the uncertainty in the reference length is calculated using the same general equation as given in eq. (D-8) with the individual components handled per paras. D-4.1 through D-4.3.

D-4.1 Reference Length Calibration Uncertainty

There are several ways to evaluate the calibration uncertainty of point-to-point reference lengths, $u_{\text{cal}}(L_{\text{ref}}^0)$ (notation described in para. D-3.1), using an integral IFM subsystem that has passed one of the tests of para. 6.4.2.

(a) *Based on the IFM Uncertainty Calibrated per ASME B89.1.8.* If the IFM is calibrated per ASME B89.1.8, the maximum error, e_{max} , of a radial measurement of a reference length of nominal value, L_{ref} , is $e_{\text{max}} = D + \text{LDE}(L_{\text{ref}})$, where D is a drift component and $\text{LDE}(L_{\text{ref}})$ is a length-dependent term. The standard uncertainty $u(L_{\text{ref}})$ is then evaluated by assigning a uniform distribution of width to the possible measurement error, so that $u_{\text{cal}}(L_{\text{ref}}^0) = e_{\text{max}}/\sqrt{3}$.

(b) *Based on the IFM Uncertainty Tested by a Set of Reference Lengths.* If the IFM is tested using a set of separately calibrated reference lengths, the uncertainty of a measured reference length, L_{ref} , can be assigned based on the observed distribution of errors in the IFM test. A suggested way of doing this is as follows:

Assume that measurement of a set of calibrated lengths, L_1, \dots, L_N (provided N is not small), yields a corresponding set of observed errors, E_1, \dots, E_N . The relative errors (i.e., fractional errors), regardless of sign, for these results are r_1, \dots, r_N where $r_k = |E_k|/L_k$, $k = 1, \dots, N$. The largest relative error, $r_{\text{max}} = \max(r_k)$, is a reasonable estimate of the maximum relative error that might occur when measuring an unknown reference length, L_{ref} . This maximum error is then estimated by $e_{\text{ref}} = (r_{\text{max}})(L_{\text{ref}})$, and assigning a uniform distribution of width, $2(r_{\text{ref}})(L_{\text{ref}})$, yields a standard uncertainty of $u_{\text{cal}}(L_{\text{ref}}^0) = (r_{\text{max}})(L_{\text{ref}})/\sqrt{3}$.

NOTE: If the IFM is tested using a set of short calibrated lengths and the non-length-dependent component of the IFM error is significant, the maximum observed relative error could be unreasonably large when extrapolated to a nominal 2.3 m reference length. In this case, it would be better to test the IFM subsystem using calibrated lengths within 20% of the nominal length of 2.3 m.

(c) *Using the Laser Tracker MPE.* If the IFM of a laser tracker has passed the ranging tests described in para. 6.4.2, the standard uncertainty, $u_{\text{cal}}(L_{\text{ref}}^0)$, is then evaluated by assigning a uniform distribution of width equal to the maximum permissible error for the length L_{ref}^0 so that $u_{\text{cal}}(L_{\text{ref}}^0) = \text{MPE}/\sqrt{3}$. In this case, it is desirable that one of the user-selected positions in Table 6.4.1-1 be nominally equal to the value of the reference length, L_{ref} , that is being calibrated.

(d) *Evaluation of Laser Uncertainty Based on First Principles.* The uncertainty of a radial displacement measurement of a reference length can be evaluated from first principles using known properties of laser beams propagating in air.

From the basic physics of displacement interferometry, the connection to the SI definition of the meter using an IFM subsystem is via the vacuum wavelength, λ_{vac} , of the laser source. Most commercial laser trackers use a frequency stabilized helium-neon laser whose λ_{vac} is known and controlled to a relative uncertainty of 1 part in 10^7 or

better. Operating in air, the component of measurement uncertainty due to uncertainty in λ_{vac} is thus generally negligible, being dominated by components due to air temperature and pressure uncertainties along the beam path. In such a case, the uncertainty in a realized reference length is evaluated as follows.

The laser tracker IFM reports a measured length, L_m , that has been compensated for the effects of ambient air temperature, pressure, and humidity on the laser wavelength (see [Nonmandatory Appendix C](#)). The compensation is based on sensor data from the laser tracker's weather station. The reference length, L_{ref}^0 , is then given by

$$L_{\text{ref}}^0 = L_m(1 - c_P\Delta P - c_T\Delta T) \quad (\text{D-9})$$

In [eq. \(D-9\)](#), $c_P\Delta P$ and $c_T\Delta T$ are corrections for possible differences $\Delta P = P - P^*$ and $\Delta T = T - T^*$ between the average air pressure, P , and temperature, T , along the IFM beam path and the sensor values P^* and T^* used in the calculation of the wavelength compensation.³ For example, there might be a temperature gradient along the beam path, while the weather station sensor measures temperature only at a single point. From [Nonmandatory Appendix C](#), for a wavelength ≈ 633 nm, the coefficients c_P and c_T are given by

$$c_P = 2.7 \times 10^{-9} \text{Pa}^{-1}$$

$$c_T = -1.0 \times 10^{-6} \text{C}^{-1}$$

In the case where the signs of the differences ΔP and ΔT are unknown, the best estimates of these quantities are taken to be zero, so that, from [eq. \(D-9\)](#), the best estimate of the reference value is

$$(L_{\text{ref}}^0)_{\text{est}} = L_m \quad (\text{D-10})$$

The standard uncertainty $u_{\text{cal}}(L_{\text{ref}}^0)$ associated with the best estimate is computed using the law of propagation of uncertainty (see [eq. D-11](#)).

$$u_{\text{cal}}(L_{\text{ref}}^0) = \sqrt{u^2(L_m) + L_m^2[c_P^2 u^2(\Delta P) + c_T^2 u^2(\Delta T)]} \quad (\text{D-11})$$

Because the vacuum wavelength is known and controlled to a relative uncertainty of 1 part in 10^7 or better, the uncertainty in the length L_m is considered negligible. That is, the effect of deviations in actual air temperature and pressure are the dominant terms. Hence,

$$u_{\text{cal}}(L_{\text{ref}}^0) = L_m \sqrt{c_P^2 u^2(\Delta P) + c_T^2 u^2(\Delta T)} \quad (\text{D-12})$$

Maximum absolute values for the pressure and temperature deviations, $|\Delta P|_{\text{max}}$ and $|\Delta T|_{\text{max}}$, are estimated, given the particular environment in which the testing is being performed. These deviations are then assigned uniform probability distributions, with

$$u(\Delta P) = |\Delta P|_{\text{max}} / \sqrt{3} \quad (\text{D-13})$$

and

$$u(\Delta T) = |\Delta T|_{\text{max}} / \sqrt{3} \quad (\text{D-14})$$

The standard calibration uncertainty of the reference length is then

$$u_{\text{cal}}(L_{\text{ref}}^0) = L_m \sqrt{\frac{c_P^2 |\Delta P|_{\text{max}}^2}{3} + \frac{c_T^2 |\Delta T|_{\text{max}}^2}{3}} \quad (\text{D-15})$$

³The effect of a possible humidity error is assumed to be negligible.

D-4.2 Uncertainty of the Reference Length Due to a Temperature Difference From the Calibration Temperature

This section applies to the specific case of an IFM used to calibrate the distance between kinematic nests located near the ends of a scale bar. If the temperature at the time of IFM calibration was recorded as T_0 , then the reference length at a different temperature, T , could be computed using eq. (D-5). In this case, the uncertainties u_{CTE} and u_T would be computed as in eqs. (D-6) and (D-7).

However, one advantage of using the laser tracker IFM is that it allows in situ calibrations that are used with a short time elapsing between calibration and test measurement. In this case, one may simply assume that the temperature at the time of test, T , is equal to T_0 , to within some maximum deviation, $|\delta T|_{\max}$. In this case, there is no correction made to obtain L_{ref} , and u_{CTE} is evaluated by the following second-order formula:

$$\begin{aligned} u_{CTE}(L_{\text{ref}}) &= L_{\text{ref}}^0 u(T) u(\alpha) \\ &= L_{\text{ref}}^0 |\delta T|_{\max} u(\alpha) / \sqrt{3} \end{aligned} \quad (\text{D-16})$$

and u_T is evaluated using eq. (D-17),

$$\begin{aligned} u_T(L_{\text{ref}}) &= \alpha(L_{\text{ref}}^0) u(T) \\ &= \alpha(L_{\text{ref}}^0) |\delta T|_{\max} / \sqrt{3} \end{aligned} \quad (\text{D-17})$$

If the duration of testing is sufficiently small that $|\delta T|_{\max}$ is small, the terms $u_{CTE}(L_{\text{ref}})$ and $u_T(L_{\text{ref}})$ could even be negligible. The reference length can be recalibrated using the IFM as necessary throughout the test to help ensure that these terms are small in order to meet the $C_m \geq 4$ requirement.

D-4.3 Other Contributors to Uncertainty in the Reference Length

The uncertainty sources described in paras. D-3.3 through D-3.6 may also contribute to uncertainty in the reference length. When the calibration is performed near the time of testing, the effects of humidity variations on the reference length will likely be negligible.

The orientation and mounting variations between reference length calibration and testing should be considered. However, it may be possible to eliminate the fixturing component of uncertainty, and possibly even the orientation component, if these are not different between the IFM calibration and the test measurement.

Usually, the SMRs themselves will have to be oriented differently during IFM calibration than during testing. This difference should be accounted for in the $u_{SMR}(L_{\text{ref}})$ unless the level of quality of the SMR makes this uncertainty component negligible compared to other terms.

D-4.4 Example

The IFM of a laser tracker is aligned to perform a radial measurement (constant IFM beam direction) of the distance between a pair of kinematic target nests. The result of the measurement is $L_m = 3.215$ m, which is taken to be the best estimate of a reference length, L_{ref} , to be used in subsequent performance evaluation tests. The manufacturer's stated MPE specification for a nominal length of 3.2 m is 50 μm .

Given the locations of the laser tracker environmental sensors and the particular test environment, maximum air pressure and temperature deviations along the beam path are estimated to be $|\Delta P|_{\max} = 3$ mmHg ≈ 400 Pa, and $|\Delta T|_{\max} = 2^\circ\text{C}$. Using a first-principles approach [see para. D-4.1(d)], the standard uncertainty is then calculated using eq. (D-15) as follows:

$$\begin{aligned} u_{\text{cal}}(L_{\text{ref}}^0) &= (3.215 \text{ m}) \sqrt{\frac{(2.7 \times 10^{-9})^2 (400)^2 + (1 \times 10^{-6})^2 (2)^2}{3}} \\ &\approx 4.2 \mu\text{m} \end{aligned}$$

By mutual agreement between the manufacturer and the user, the user provides the SMR for the calibration of the reference length and subsequent performance testing. The MPE specifications for the laser tracker under test are only valid for high-accuracy SMRs (centering errors smaller than 2 μm) whereas the SMR provided by the user has centering errors as large as ± 5 μm . Because the calibration of the reference length was performed with the SMR in the same orientation with respect to the laser beam, the centering error is common mode at the two nests and cancels out. However, because the SMR is oriented differently during the performance testing, the uncertainty due to the SMR centering error is accounted for in the test value uncertainty. Assuming 5 μm as the bound for a rectangular distribution,

the standard uncertainty in the reference length due to centering error is $u_{\text{SMR}}(L_{\text{ref}}) = \frac{5}{\sqrt{3}}\sqrt{2} = 4.1 \mu\text{m}$, where the factor of $\sqrt{2}$ arises from the fact that the SMR centering error affects the length measurement at each of the two ends.

The uncertainty in the reference length is the root-sum-squared value of the two previously determined standard uncertainty values, thus,

$$\begin{aligned} u(L_{\text{ref}}) &= \sqrt{[u_{\text{cal}}(L_{\text{r}}^0)]^2 + [u_{\text{SMR}}(L_{\text{ref}})]^2} \\ &= 5.9 \mu\text{m} \end{aligned}$$

Then, per [section D-2](#), the measurement capability index is

$$\begin{aligned} C_m &= \frac{\text{MPE}}{2u(L_{\text{ref}})} \\ &= \frac{50\mu\text{m}}{8.4\mu\text{m}} \\ &\approx 4.2 \end{aligned}$$

Thus, $C_m > 4$, and the realized reference length may be used for point-to-point length measurement systems tests. Other sources of uncertainty discussed in [paras. D-3.3](#) through [D-3.5](#) are negligible in this example.

D-5 REFERENCE LENGTH REALIZED USING TARGET NESTS CALIBRATED USING AN ADM

In this method of realizing a reference length, a kinematic nest for an SMR is mounted on each of two stable structures, such as the commercially available tripod stands used for mounting optical tooling. The kinematic nests may also be near the ends of a scale bar. For laser trackers that include an ADM that has passed one of the test procedures of [para. 6.4.3](#), the ADM may be used to establish the reference length. The ADM beam is aligned parallel to the line joining the two kinematic nests so that the tracker measures in a purely radial direction, and the ADM measures the displacement of an SMR as it is moved from one nest to the other. This measured displacement is the reference length realized by the two SMR positions.

D-5.1 Reference Length Uncertainty

If the laser tracker ADM has passed the ranging tests described in [para. 6.4.3](#), the standard uncertainty, $u_{\text{cal}}(L_{\text{ref}}^0)$, is then evaluated by assigning a uniform distribution of width equal to the maximum permissible error for the length, L_{ref}^0 , so that $u_{\text{cal}}(L_{\text{ref}}^0) = \text{MPE}/\sqrt{3}$. In this case, it is desirable that one of the user-selected positions in [Table 6.4.1-1](#) be nominally equal to the value of the reference length, L_{ref} , that is being calibrated.

D-5.2 Other Contributors to Uncertainty in the Reference Length

Uncertainty contributors described in [paras. D-4.2](#) and [D-4.3](#) may also apply in this case.

D-6 REALIZATION OF REFERENCE LENGTHS USING A LASER RAIL SYSTEM

A laser rail system containing a separate displacement interferometer, external to the laser tracker, can be used to establish reference lengths, which are typically established simultaneously to a laser tracker test measurement. A schematic of such a laser rail system is shown in [Figure D-6-1](#). Typically, two SMR targets are mounted on the laser rail carriage. One is used by an external laser interferometer to measure the displacement of the carriage, and the second is the target for the laser tracker under test.

Care should be taken to ensure proper alignment of the laser rail system; incorrect alignment can result in the reference interferometer and the laser tracker measuring different quantities. These differences are caused primarily by Abbé errors due to offsets of the laser tracker SMR relative to the reference interferometer measurement beam. This error source, which is specific to the reference lengths produced using a laser rail system, is described in detail in [para. D-6.2](#) and is combined with other sources of uncertainty used to evaluate the standard uncertainty associated with reference lengths produced using a laser rail. Details of such laser rail systems can be found in "A Laser Tracker Calibration System."⁴

⁴D. Sawyer et al., "A Laser Tracker Calibration System," published in the proceedings of the 2002 Measurement Science Conference.

the standard uncertainty in the reference length due to centering error is $u_{\text{SMR}}(L_{\text{ref}}) = \frac{5}{\sqrt{3}}\sqrt{2} = 4.1 \mu\text{m}$, where the factor of $\sqrt{2}$ arises from the fact that the SMR centering error affects the length measurement at each of the two ends.

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Uncertainty contributors described in [paras. D-4.2](#) and [D-4.3](#) may also apply in this case.

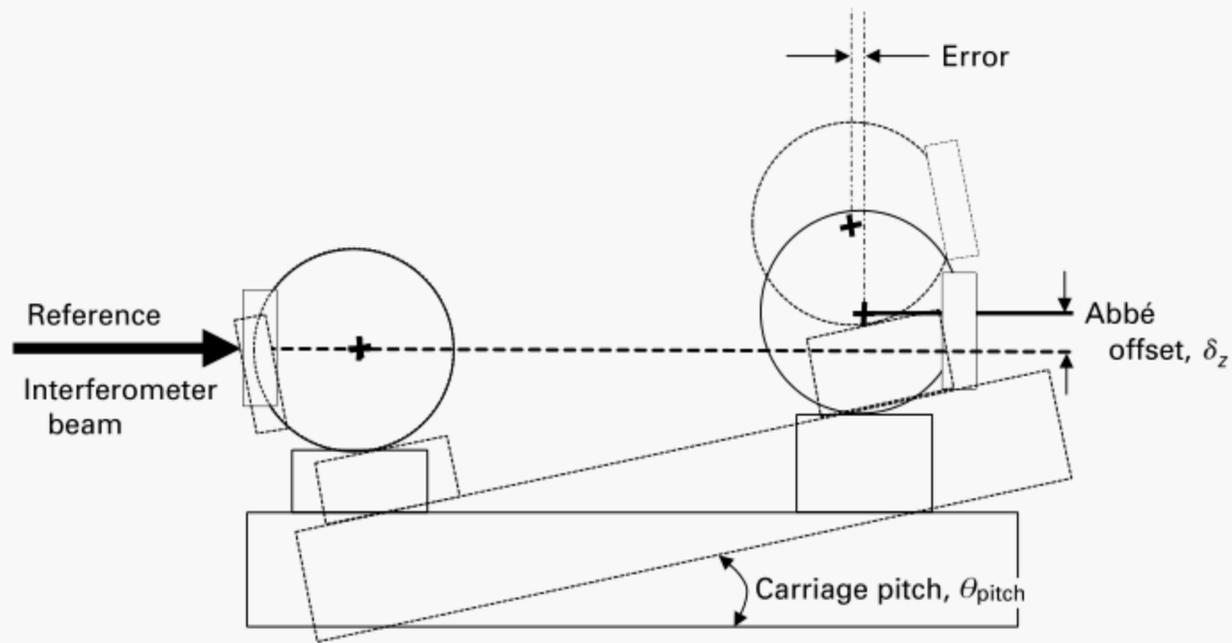
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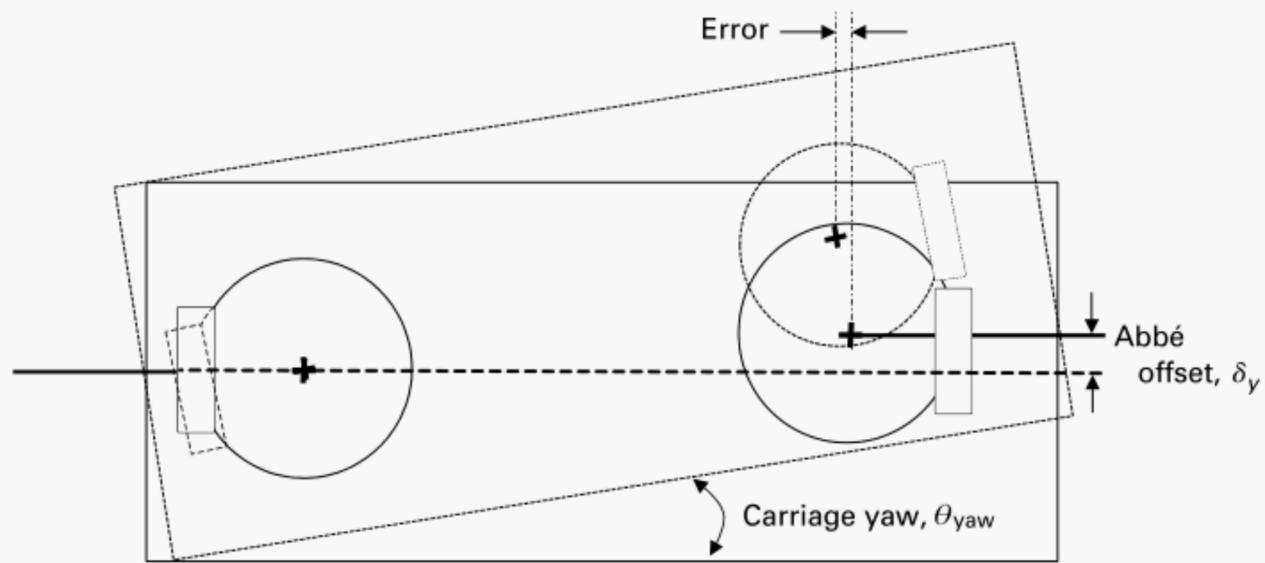
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Figure D-6.2-1
Illustrating the Origin of Abbé Errors



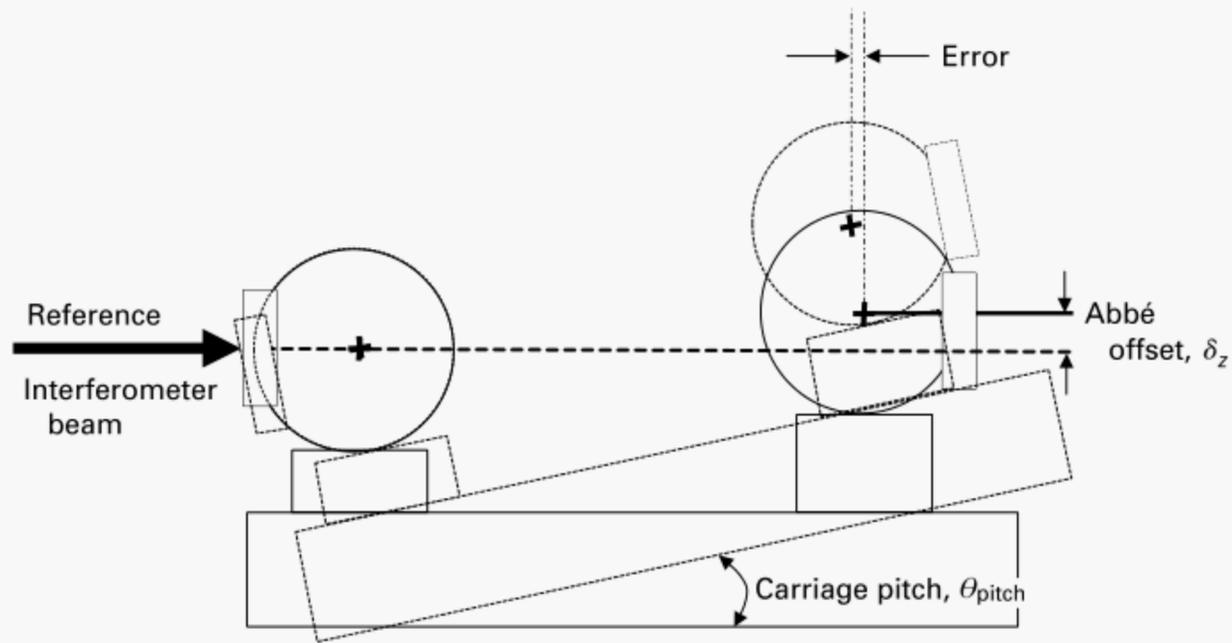
(a) Side View



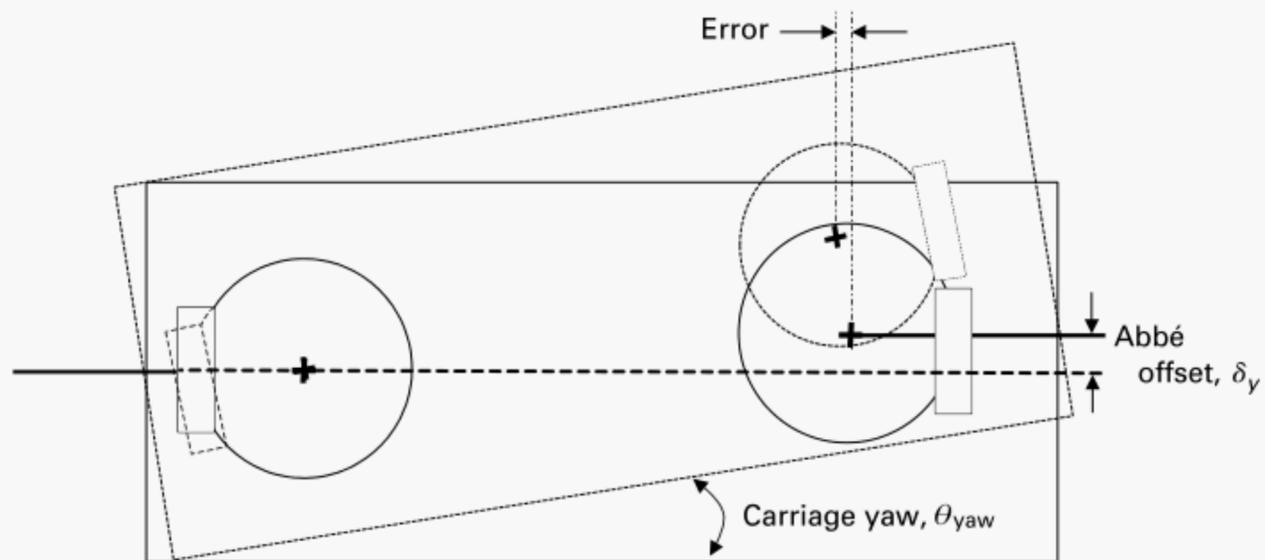
(b) Top View

GENERAL NOTE: The solid and dashed lines show the orientation of the carriage in the initial and final positions, respectively. The target positions have been superimposed to illustrate the source of the Abbé error. All offsets and angular orientations have been exaggerated for clarity.

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Illustrating the Origin of Abbé Errors



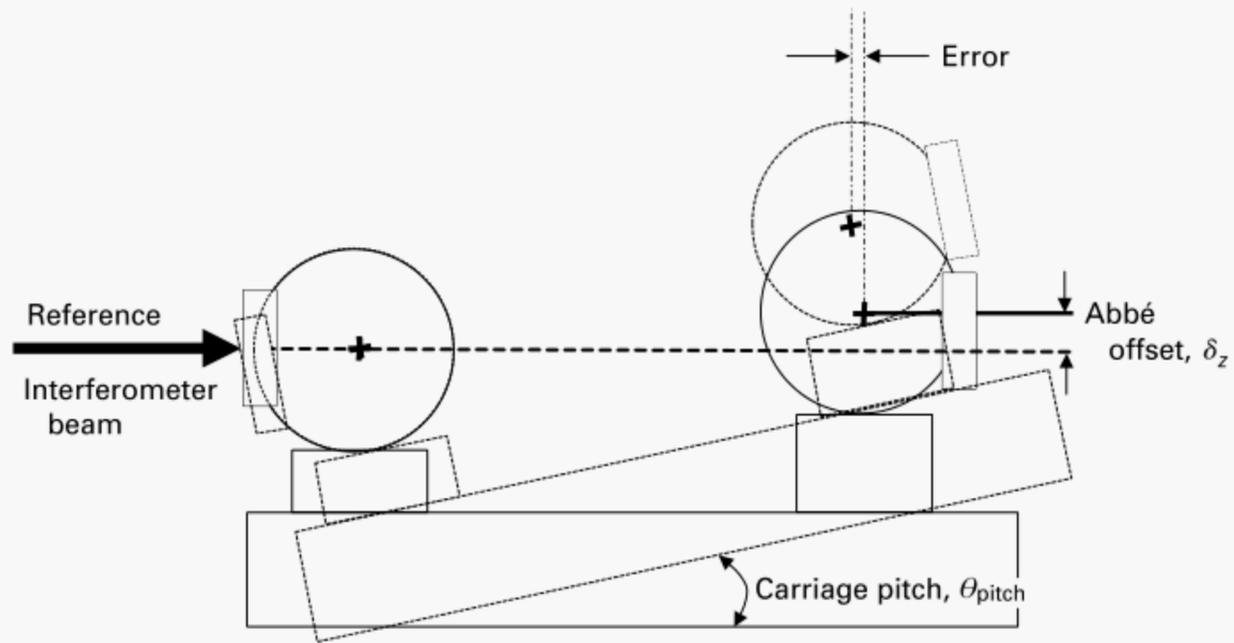
(a) Side View



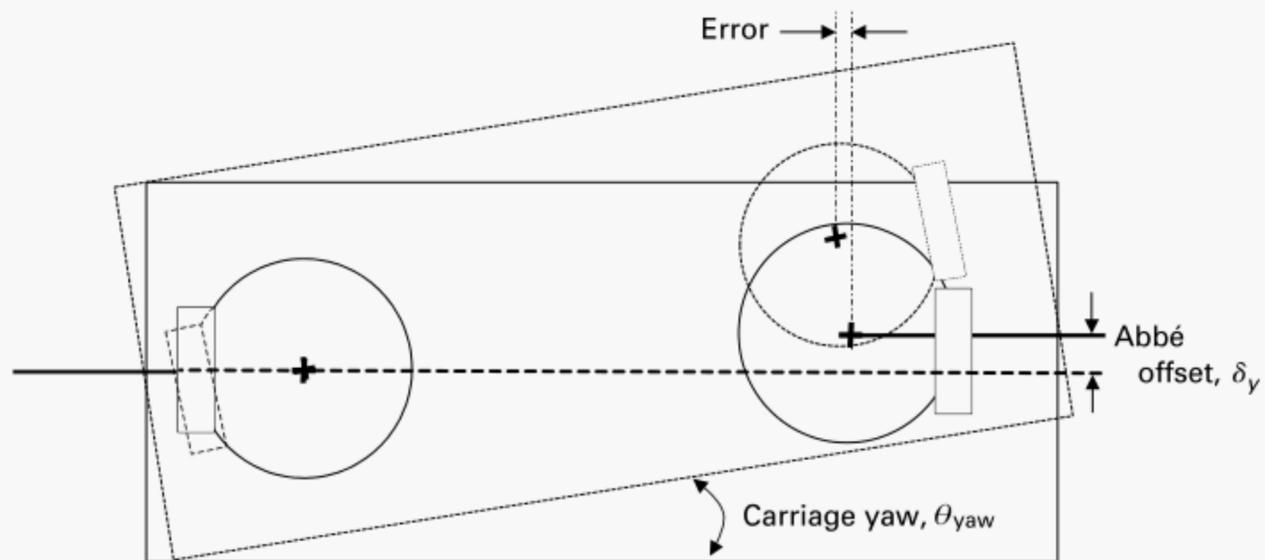
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Illustrating the Origin of Abbé Errors



(a) Side View



(b) Top View

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NONMANDATORY APPENDIX E

EFFECT OF AIR TEMPERATURE ON LASER TRACKER MEASUREMENTS

E-1 INTRODUCTION

(21)

The test procedures of this Standard require that laser tracker specifications be accompanied by rated operating conditions, which include environmental conditions such as minimum temperature, maximum temperature, and temperature gradients (spatial gradients in degrees Celsius per meter and temporal gradients in degrees Celsius per hour). However, these values may be insufficient to fully characterize the errors in laser tracker measurements caused by temperature variations. This Appendix describes how to precisely quantify one particular type of laser tracker error: the error that is caused by refraction and retardation along the beam path. The procedure does not account for other types of temperature-related errors, such as those that might arise from the bending or thermal deformation of the laser tracker.

It is important to have a quantitative description of the effects of air temperature on a laser beam. This enables one to calculate the uncertainty of laser tracker measurements, whether performed in a calibration laboratory or a production environment.

E-2 RADIAL AND TRANSVERSE ERRORS

Different equations are used to quantify the errors in the radial and transverse directions. The equation for the radial error is based on a simple physical argument. The equation for the transverse error is derived from the ray equation.

E-2.1 Equations for Radial Error

A laser tracker is set up to measure the displacement, d , between two points, P_1 to P_2 . The true displacement is

$$d = \int_{P_1}^{P_2} ds \quad (\text{E-1})$$

where ds is a length element along the beam path.

The laser tracker contains one or more sensors that measure the temperature, T_m , of the air. It also generates a laser beam that it sends through the air. At the position s , the air has a temperature of $T(s)$, and the laser beam has a speed of $c/n[T(s)]$, where c is the speed of light in vacuum and $n[T(s)]$ is the refractive index of the air at the temperature T and position s .

The interferometer (IFM) or absolute distance meter (ADM) within the laser tracker determines the displacement, d_m , by measuring the optical path distance (OPD) and dividing this by the estimated refractive index, $n(T_m)$, as follows:

$$d_m = \frac{1}{n(T_m)} \int_{P_1}^{P_2} n[T(s)] ds \quad (\text{E-2})$$

The laser beam deviates only slightly from a straight line so that the paraxial approximation is valid. The beam is assumed to propagate in the z direction, so that s may be replaced by z as follows:

$$d_m = \frac{1}{n(T_m)} \int_{P_1}^{P_2} n[T(z)] dz \quad (\text{E-3})$$

The refractive index is expanded about its value at temperature T_m ,

$$d_m = \frac{1}{n(T_m)} \int_{P_1}^{P_2} \left[n(T_m) + \frac{\partial n}{\partial T} \delta T(z) \right] dz \quad (\text{E-4})$$

where $\delta T(z) = T(z) - T_m$. The quantity $\partial n/\partial T$ is approximately constant for small changes in temperature so that the last equation simplifies to

$$d_m = d \left[1 + \frac{\overline{\delta T}}{n(T_m)} \frac{\partial n}{\partial T} \right] \quad (\text{E-5})$$

where $\overline{\delta T}$ is the average of δT over the path from P_1 to P_2 .

The fractional error in the radial direction, e_R is then

$$e_R = \frac{\overline{\delta T}}{n(T_m)} \frac{\partial n}{\partial T} \quad (\text{E-6})$$

As an example, suppose that at the wavelength and environmental conditions under consideration, the sensitivity of the refractive index to a change in temperature is $\partial n/\partial T = -1 \times 10^{-6} \text{C}^{-1}$. Also assume that the laser tracker temperature sensor reads 20°C , while the average temperature over the path of the laser beam is 21.5°C . The refractive index is approximately equal to 1. The fractional error is then approximately

$$e_R = \frac{-(21.5 - 20)}{1} \times 10^{-6} = -1.5 \times 10^{-6} \quad (\text{E-7})$$

If the distance to the target were 10 m, the radial error would be $-15 \mu\text{m}$. The minus sign means that the target is $15 \mu\text{m}$ farther from the laser tracker than indicated by the radial displacement measurement.

E-2.2 Equations for Transverse Error

The formulas for the transverse error are derived from the ray equation. The general form of this equation is

$$\nabla n = \frac{d}{ds} \left(n \frac{dr}{ds} \right) \quad (\text{E-8})$$

where

- ds = length element along the trajectory
- n = refractive index
- r = position along the trajectory

Detailed discussions of optical ray propagation may be found in Principles of Optics¹ and Fundamentals of Photonics.²

The beam from a laser tracker deviates little from a straight line. The paraxial approximation is therefore valid, and s can be replaced by z in eq. (E-8). Furthermore, the vector equation can be written as two scalar equations as follows:

$$\frac{d}{dz} \left(n \frac{dx}{dz} \right) = \frac{\partial n}{\partial x} \quad (\text{E-9})$$

$$\frac{d}{dz} \left(n \frac{dy}{dz} \right) = \frac{\partial n}{\partial y} \quad (\text{E-10})$$

In these equations, the laser beam points at least approximately along the z -axis. The slopes of the ray in the x and y directions are dx/dz and dy/dz . The term on the right side of eq. (E-9) is expanded, and the equation is integrated from $z = z_i$ to $z = z'$ and divided by n . The result is

$$\frac{dx}{dz} \Big|_{z'} = \frac{n(z_i)}{n(z')} \frac{dx}{dz} \Big|_{z_i} + \frac{1}{n(z')} \int_{z_i}^{z'} \frac{\partial n}{\partial T} \frac{\partial T}{\partial x} dz \quad (\text{E-11})$$

If the final point is z_f , this equation is rewritten as

¹ Born, M., and Wolf, E., Principles of Optics, Cambridge University Press, 1999.

² Saleh, B. E. A., and Teich, M. C., Fundamentals of Photonics, Wiley, 1991.

$$\left. \frac{dx}{dz} \right|_{z_f} = \left. \frac{n(z_i)}{n(z_f)} \frac{dx}{dz} \right|_{z_i} + \frac{1}{n(z_f)} \int_{z_i}^{z_f} \frac{\partial n}{\partial T} \frac{\partial T}{\partial x} dz \quad (\text{E-12})$$

This represents the slope (angle) of the ray in the x direction. All of the quantities on the right side of the equation can be measured or are known. The temperature $T(x, y, z)$ can be measured as a function of position, which gives the gradient $\partial T/\partial x$. This same temperature information, along with the Ciddor equation (see [Nonmandatory Appendix C](#)), provides the values $n(z_i)$, $n(z_f)$, and $\partial n/\partial T$. The quantity $(dx/dz)_{z_i}$ is the initial slope (angle) of the ray.

To find the displacement Δx of the laser beam in the x direction, [eq. \(E-11\)](#) is integrated from $z = z_i$ to $z = z_f$. The result is

$$\Delta x = n(z_i) \left. \frac{dx}{dz} \right|_{z_i} \int_{z_i}^{z_f} \frac{dz'}{n(z')} + \int_{z_i}^{z_f} \frac{1}{n(z')} \int_{z_i}^{z'} \frac{\partial n}{\partial T} \frac{\partial T}{\partial x} dz dz' \quad (\text{E-13})$$

[Equations \(E-11\)](#) and [\(E-13\)](#) quantify the transverse displacement of the laser beam (refraction) as a result of thermal gradients.

E-2.3 Example

A laser tracker sends a laser beam parallel to a production floor. The floor is colder than the air above it, and there is a thermal gradient of $\partial T/\partial x = +1^\circ\text{C} \times \text{m}^{-1}$ in the vertical (x) direction over most of the floor. For a short distance the laser beam passes below a heat source. The environmental conditions along the beam path are

$$\frac{\partial T}{\partial x} = \begin{cases} +1^\circ\text{C} \times \text{m}^{-1}, & 0 \text{ m} \leq z < 4 \text{ m} \\ +10^\circ\text{C} \times \text{m}^{-1}, & 4 \text{ m} \leq z < 5 \text{ m} \\ +1^\circ\text{C} \times \text{m}^{-1}, & 5 \text{ m} \leq z < 10 \text{ m} \end{cases} \quad (\text{E-14})$$

$$\frac{\partial n}{\partial T} = -1 \times 10^{-6} \text{ } ^\circ\text{C}^{-1} \quad (\text{E-15})$$

At $z = 10 \text{ m}$, the laser beam is returned by a retroreflector.

Problem: Find the angle and displacement of the laser beam in the x direction at all distances to and from the retroreflector.

Solution: Let the initial angle of the beam with respect to the z -axis be zero. When the laser beam arrives at $z = 10 \text{ m}$, the sign of the slope (angle) is reversed and the calculation is completed for the round trip to the laser tracker. The refractive index is approximately 1 at all distances z . The angle and displacement are calculated using [eqs. \(E-12\)](#) and [\(E-13\)](#), yielding the results shown in [Figures E-2.3-1](#), [E-2.3-2](#), and [E-2.3-3](#).

Note that angle dx/dz is found by integrating the gradient over the distance z , and the transverse displacement Δx is found by integrating the angle dx/dz over the same distance. This is reminiscent of finding velocity by integrating acceleration and finding position by integrating velocity. The similarity is not surprising when one compares the ray equation [[eq. \(E-9\)](#)] to the equation for Newton's second law.

$$\frac{d}{dt} \left(m \frac{dx}{dt} \right) = F_x \quad (\text{E-16})$$

For simplicity, consider the special case in which the refractive index, n , and the mass, m , are constants. The following table compares the analogous quantities in [eqs. \(E-9\)](#) and [\(E-16\)](#):

Equation (E-9), the Ray Equation

Gradient, $\partial n/\partial x$

Distance, z

Displacement, x

Equation (E-16), Newton's Second Law

Acceleration, F_x/m

Time, t

Displacement, x

If z is the distance traveled by the laser beam, the fractional error, e_x , in the transverse direction is

$$e_x = \Delta x/z \quad (\text{E-17})$$

The fractional error for the example above is shown in [Figure E-2.3-4](#).

If the gradient retains the same sign (positive or negative) as it travels, the fractional error will tend to increase as the distance z increases. In [Figure E-2.3-4](#), notice that the fractional error increases linearly from 0×10^{-6} to 2×10^{-6} over the first 4 m. For the case in which the gradient $\partial n/\partial x$ is constant, the fractional error is

$$e_x = \frac{z}{2} \frac{\partial n}{\partial x} \quad (\text{E-18})$$

When the gradient is not constant, the fractional error is not so easily calculated. It depends not only on the distance traveled and the average gradient, but also on the particular gradient distribution. If the gradients near the laser tracker are larger than those far away, the fractional error will be larger than in the reverse situation.

For the case in which the gradient is not constant, it is useful to define the maximum effective gradient as

$$\left| \frac{\partial n}{\partial x} \right|_{\text{max effect}} = \frac{z}{2} \times |e_x|_{\text{max slope}} \quad (\text{E-19})$$

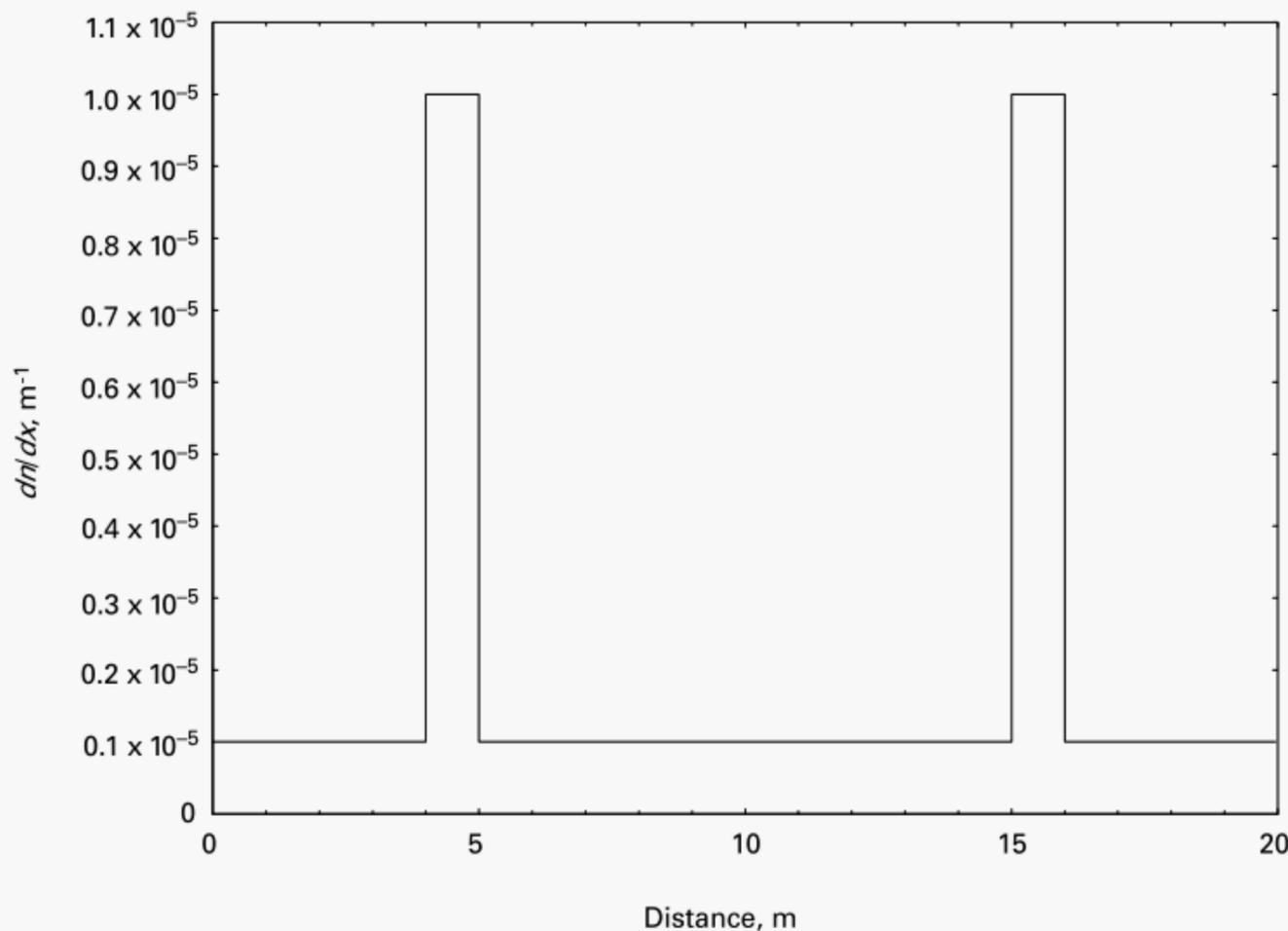
The last term in this equation is the absolute value of the fractional error at that point where the slope of a line starting at the origin is greatest. In [Figure E-2.3-4](#), this point is found at $z = 10$ m, where the fractional error is 9.95×10^{-6} . The maximum effective gradient is therefore equal to $9.95 \times 10^{-6}/5 \text{ m} = 1.99 \times 10^{-6} \text{ m}^{-1}$.

E-3 UNAMBIGUOUS ENVIRONMENTAL SPECIFICATIONS

The following two quantities precisely quantify the direct effects of air temperature variations on laser light from a laser tracker:

- (a) for radial measurements: fractional error in the radial direction, e_R , as calculated from [eq. \(E-6\)](#)
- (b) for transverse measurements: maximum effective gradient, $\partial n/\partial x_{\text{max effect}}$, as calculated from [eq. \(E-19\)](#)

Figure E-2.3-1
Change in Refractive Index Versus Transverse Distance, x



If the gradient retains the same sign (positive or negative) as it travels, the fractional error will tend to increase as the distance z increases. In Figure E-2.3-4, notice that the fractional error increases linearly from 0×10^{-6} to 2×10^{-6} over the first 4 m. For the case in which the gradient $\partial n/\partial x$ is constant, the fractional error is

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Figure E-2.3-1
Change in Refractive Index Versus Transverse Distance, x

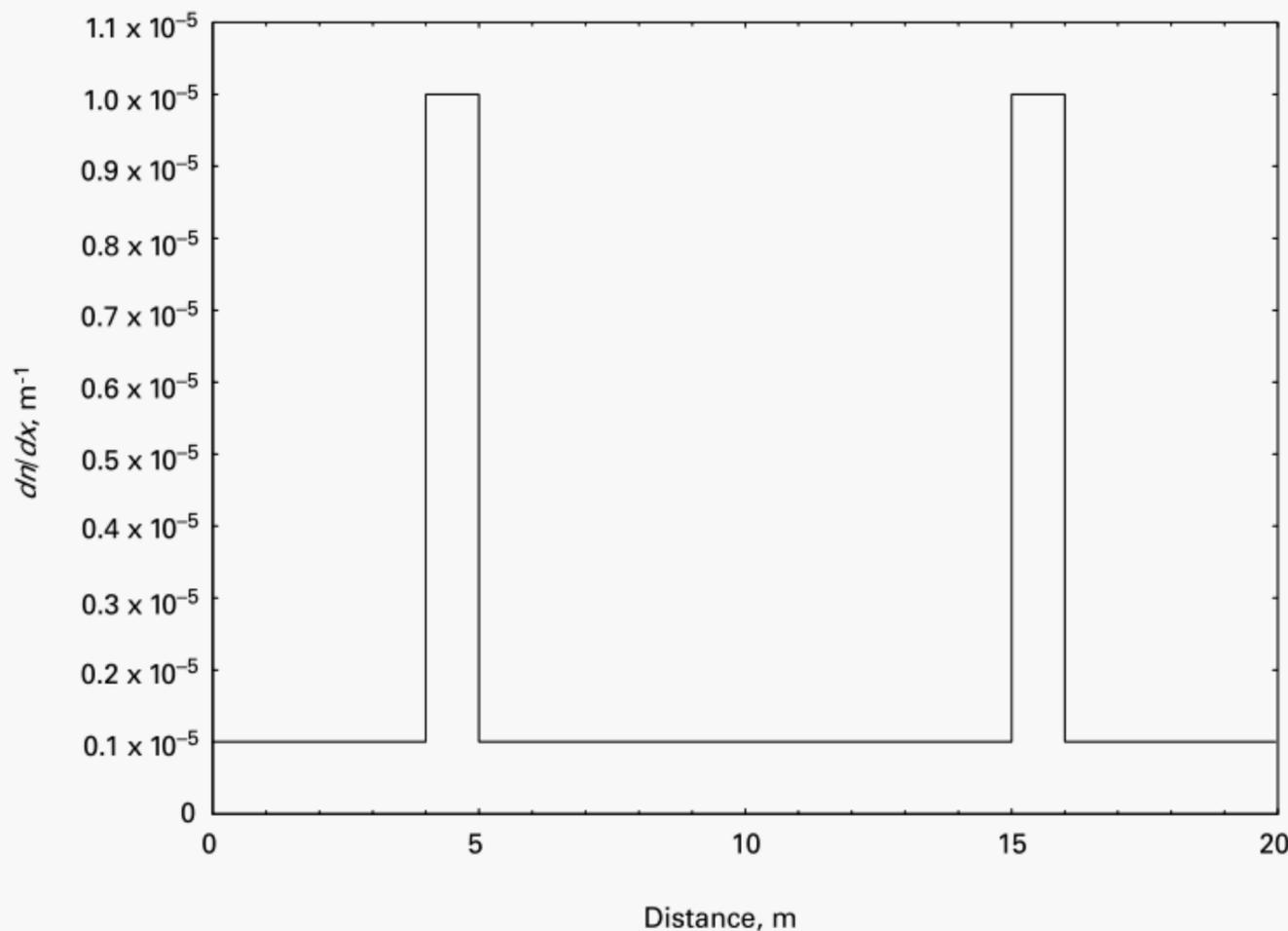
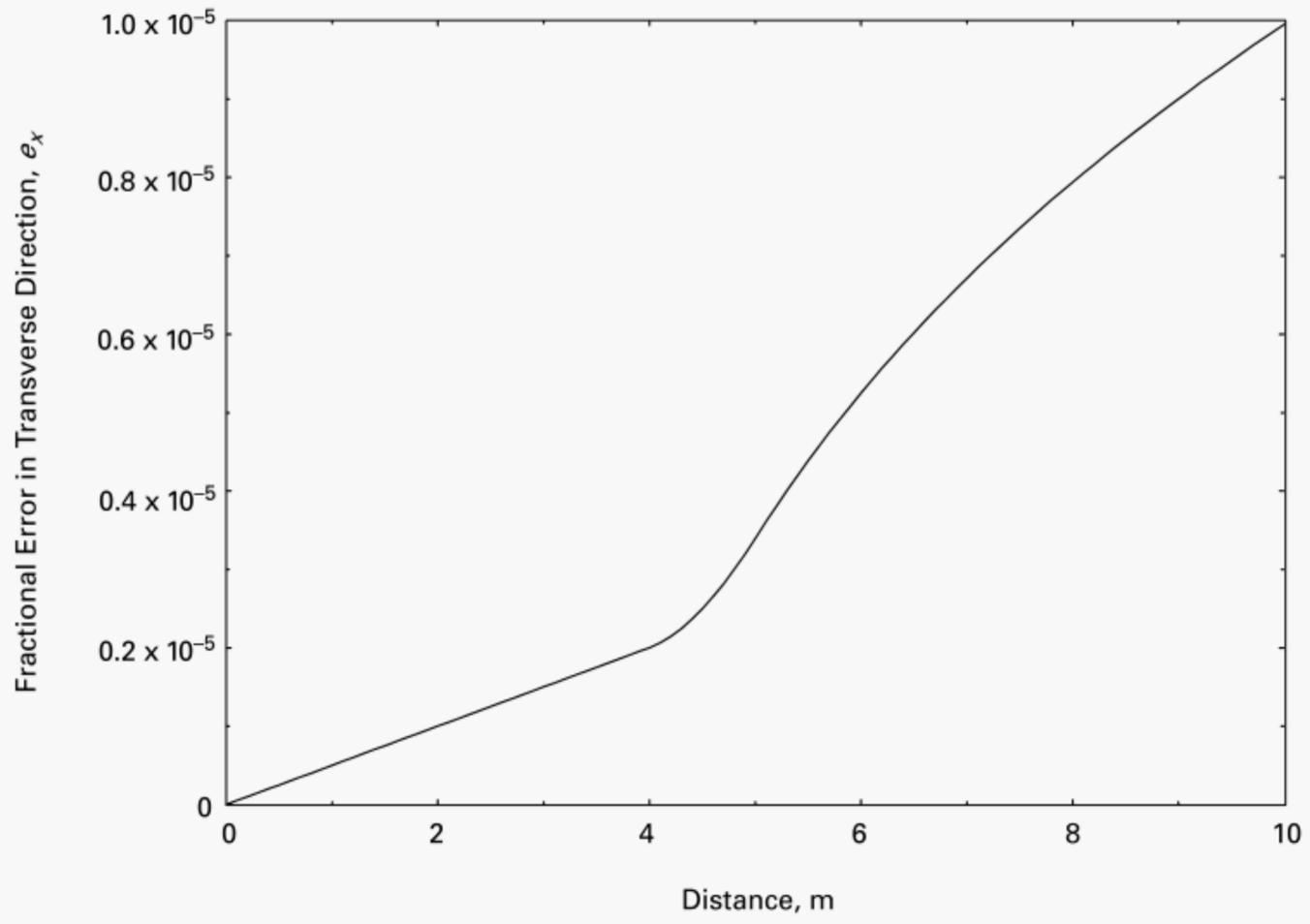


Figure E-2.3-4
Example of Fractional Error Versus Distance



NONMANDATORY APPENDIX F

LASER TRACKER INTERIM TESTING

(21)

F-1 INTRODUCTION

Interim testing is designed to ensure that a laser tracker is functioning properly between routine calibrations. Interim test procedures are expressly designed to be sensitive to changes in a laser tracker that could degrade performance to a degree that invalidates the manufacturer's performance specifications. Interim testing is not a substitute for routine calibration or error compensation.

This Appendix provides an interim test to assess the performance of a laser tracker in the field. There are two parts to this interim test. The first part (see [para. F-5.1](#)) assesses the extent of optical and geometric misalignments in the laser tracker while the second part (see [para. F-5.2](#)) assesses the inclinometer errors in the laser tracker. Depending on the needs of the user, either or both parts of the interim test may be performed.

F-2 ENVIRONMENTAL CONSIDERATIONS

Interim testing should be performed in an environment that is similar to the one in which the laser tracker is used in practice. If the laser tracker is used in a factory floor environment that experiences large variations in temperature and humidity, interim testing should be performed in a similar environment. This may involve performing interim tests on the shop floor at different times of the day to ensure that the entire range of applicable operating environments is sufficiently sampled during the testing. Interim testing on the shop floor allows the observation of measurement errors associated with that environment and hence provides the user with an indication of the accuracy of the laser tracker in use.

F-3 FREQUENCY OF INTERIM TESTING

The frequency of interim testing is a matter of economics and necessity, i.e., the time period between interim tests should be chosen in a manner that meets the needs of the laser tracker user while not compromising the integrity of the measurement tasks performed. This is a judgment call on the part of the user.

A laser tracker that is in a stable environment with a single user will typically need interim testing less often than one that is frequently transported, used by multiple operators, or used in a harsh environment. The frequency of testing is also strongly affected by balancing the cost of interim testing against the consequences or risks of accepting a bad workpiece or rejecting a good one. It may be useful to consider the interim testing interval as a percentage of total laser tracker operating hours. Some users with high value or safety critical workpieces may elect to perform daily tests, whereas other users might test weekly or monthly. Additionally, interim testing should be conducted after any sort of significant event, such as the tracker being subject to excessive vibrations or to potential damage.

F-4 A BEST PRACTICE GUIDELINE

Two-face tests are a quick and efficient way to assess the state of a laser tracker and are part of the mandatory portion of the performance evaluation tests as described in [para. 6.3](#). They require no calibrated artifact and are sensitive to several geometry misalignment parameters. As a general guideline on best practices, it is therefore recommended that two-face tests be performed at different points in the laser tracker's working volume on a regular basis or prior to commencing measurements. Such two-face testing provides an indication of the health of the laser tracker with minimal investment of time and effort. However, two-face tests are not sensitive to all error sources and are therefore not equivalent to the interim test described in [section F-5](#), which includes both two-face tests and length measurement tests.

F-5 INTERIM TEST PROCEDURE

The tests in this section describe a set of point-to-point length measurements, two-face measurements, and/or point coordinate measurements. In all cases, good measurement practices and proper metrological techniques should be used to ensure the integrity of the measurement results.

NONMANDATORY APPENDIX F

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F-4 A BEST PRACTICE GUIDELINE

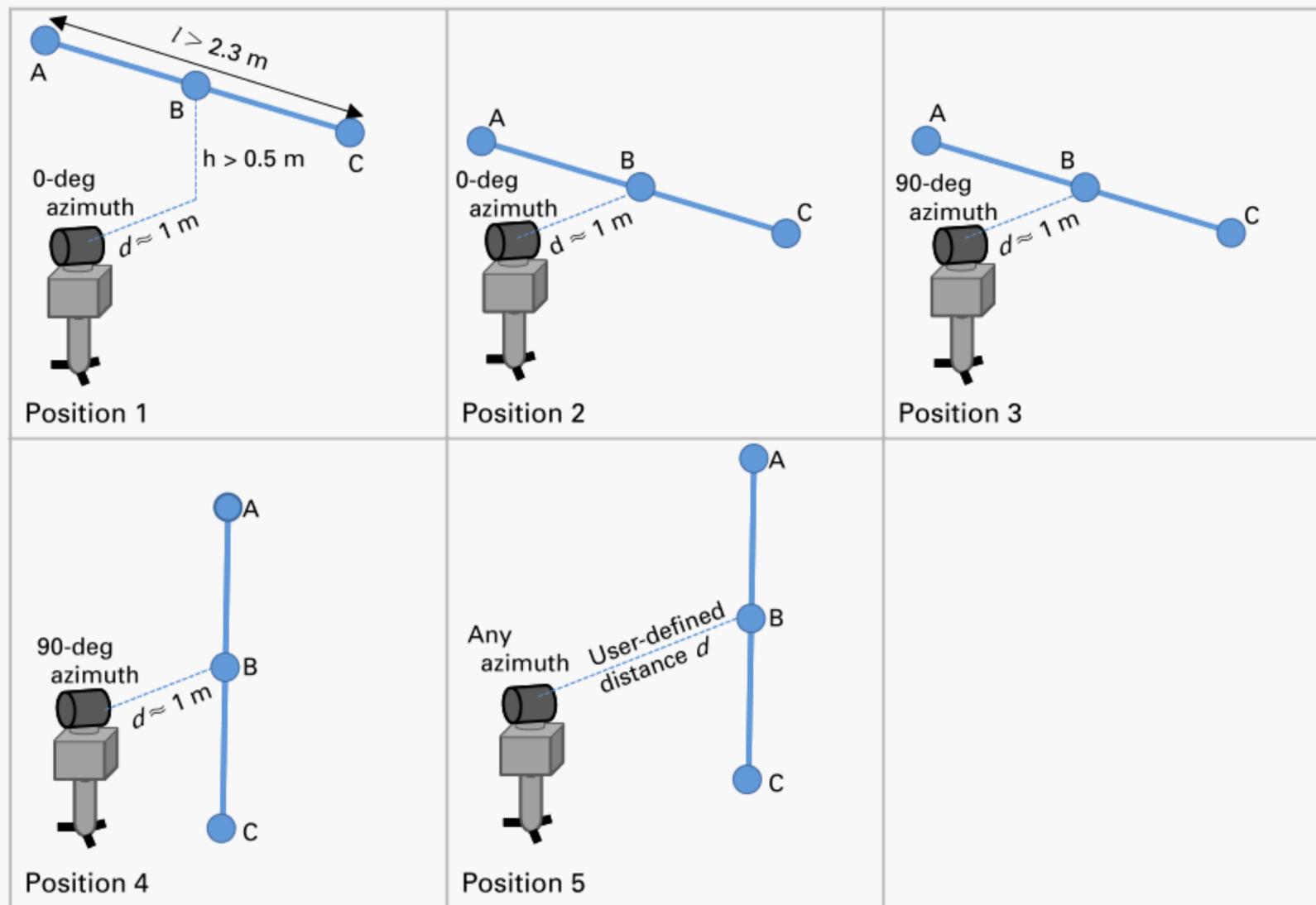
Two-face tests are a quick and efficient way to assess the state of a laser tracker and are part of the mandatory portion of the performance evaluation tests as described in [para. 6.3](#). They require no calibrated artifact and are sensitive to several geometry misalignment parameters. As a general guideline on best practices, it is therefore recommended that two-face tests be performed at different points in the laser tracker's working volume on a regular basis or prior to commencing measurements. Such two-face testing provides an indication of the health of the laser tracker with minimal investment of time and effort. However, two-face tests are not sensitive to all error sources and are therefore not equivalent to the interim test described in [section F-5](#), which includes both two-face tests and length measurement tests.

F-5 INTERIM TEST PROCEDURE

The tests in this section describe a set of point-to-point length measurements, two-face measurements, and/or point coordinate measurements. In all cases, good measurement practices and proper metrological techniques should be used to ensure the integrity of the measurement results.

Figure F-5.1.2-2
Five Test Positions to Perform the Interim Check of a Laser Tracker

(21)



GENERAL NOTES:

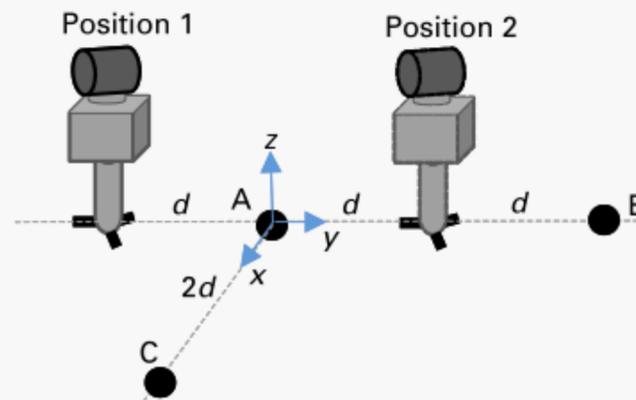
- Although positions 1 through 4 show the laser tracker at azimuth angles of 0 deg and 90 deg, any pair of angles 90 deg apart from each other are allowed.
- Nest B is located directly in front of the tracker so that the line joining the tracker and nest B is orthogonal to the line joining the three nests A, B, and C. For all positions, length AC shall be at least 2.3 m, and lengths AB and BC shall be equal and at least 1.15 m. For positions 1, 2, and 3, nests A and C shall be 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 shall be located on either side of nest B so that the nests A, B, and C form a vertical line.

When using a three-nest scale bar, it is advantageous to acquire data using both faces of the tracker so that all two-face and length measurement errors may be determined in one setup. Thus, in each of the five positions, the laser tracker measures the location of each SMR in front sight and again in back sight. Two-face errors are calculated for each of the nests A, B, and C, and for each of the five positions in Figure F-5.1.2-2. Thus, 15 two-face errors are calculated in all. Length measurement errors are calculated using measurements made in front sight only. For each of the five positions, one length measurement error is obtained while measuring the symmetrical length AC while two length measurement errors are obtained while measuring asymmetrical lengths AB and BC. Thus, 15 length measurement errors are calculated in all. All 15 two-face errors and all 15 length measurement errors should be smaller than the corresponding MPEs. Errors larger than the MPEs indicate a problem with either the laser tracker or the test setup (tripod, reference length, etc.). The source of the errors should be determined and resolved prior to using the laser tracker for measurements.

F-5.1.3 Alternate Ways of Realizing the Interim Test for Geometry Errors. While the interim test procedure for tracker geometry errors was described earlier using a three-nest scale bar, the test may be performed in other ways as well. For example, a two-nest scale bar that is at least 2.3 m long may be used to realize the symmetrical and asymmetrical lengths for each of the five positions by moving either the tracker or the scale bar. A set of nests fixed to a rigid structure (e.g., a wall) where the distance between the nests has been previously calibrated may also be used for the interim tests.

(21)

Figure F-5.2.2-1
Setup for Inclinometer Tests



F-5.2 Interim Test for Inclinometer Errors (Orient-to-Gravity Tests)

F-5.2.1 Introduction. This section describes an interim test procedure to determine the performance of the laser tracker's inclinometer sensor. There are two modes in which inclinometers are used in laser trackers. In the first and more common mode of usage, inclinometers are used to establish a gravity-aligned coordinate system in which all subsequent test object measurements are performed. In this mode of usage, the inclinometer is not read as part of every object coordinate measurement. The test for this first mode is described in [para. F-5.2.3](#). In the second mode of usage, the inclinometer is read as part of each object coordinate measurement, and the measured coordinate is transformed to a gravity-aligned coordinate system based on the current measurements of the tilt angles. The test for the second mode is described in [para. F-5.2.4](#). While the interim tests for both modes of usage involve the laser tracker and three stationary nests mounted on the ground, there are differences in the test procedures. The test setup and procedures are described in [paras. F-5.2.2](#) through [F-5.2.5](#).

As mentioned earlier in this Appendix, because interim testing and reverification testing are procedures set by the laser tracker user, the user may select any decision rule for those tests. The test value uncertainty for the inclinometer tests is negligibly small, because the three nests can be assumed to be stationary for the duration of the tests.

F-5.2.2 Setup. The setup for both interim tests for inclinometer errors is as follows:

- (a) Two nests, A and B, are placed on the floor, a distance $2d$ apart from each other as shown in [Figure F-5.2.2-1](#). The value for the distance d is recommended to be at least 1 m but not more than 5 m.
- (b) The laser tracker is placed on the line joining nests A and B, either outside at position 1 or inside at position 2. Positions 1 and 2 are at a distance, d , from nest A on the line joining nests A and B.
- (c) Nest C is placed on the floor so that AC is perpendicular to AB and the distance AC is $2d$.
- (d) The laser tracker positions shall not deviate from the line AB by an amount larger than 0.1 m. Similarly, nest C shall not deviate from its recommended location (on the x-axis in [Figure F-5.2.2-1](#)) by an amount larger than 0.1 m.

F-5.2.3 Inclinometer Test Based on Tracker Tilt. For the first mode of inclinometer usage, as described in [para. F-5.2.1](#), the test procedure involves measuring the z-coordinates of SMRs located at nests distributed on the floor in a gravity-aligned coordinate system. The laser tracker is then slightly tilted, a new gravity-aligned coordinate system is constructed, and the coordinates of the SMRs are measured again. The z-coordinates of the SMRs should remain the same if there are no inclinometer errors. To determine the magnitude of inclinometer errors, the difference in z-coordinates before and after tilt are converted to units of angle and compared against the MPEs. Because the laser tracker is tilted by a small amount while located at the same position, the errors in the vertical angle are expected to remain constant before and after tilting. Thus, the differences in the z-coordinates may be attributed entirely to the inclinometer errors.

The test procedure is as follows:

- (a) Using software provided by the manufacturer or by a third party, establish a level frame so that the z-axis of the laser tracker's coordinate system is aligned with the gravity direction. This requires measurement of the inclinometer followed by coordinate transformation from the laser tracker's base coordinate system to one whose z-axis is aligned with gravity.
- (b) Measure the coordinates of SMRs located at nests A, B, and C in the level-frame coordinate system.
- (c) Translate the coordinate system so that the origin is located at nest A.

(d) Rotate the coordinate system so that nest B lies on the YZ plane; ensure that the z-axis continues to remain aligned with the gravity direction.

(e) Record the z-coordinates of SMRs located at nests B and C, z_{B1} and z_{C1} , as measured by the tracker in the coordinate system established in (d).

(f) While keeping the laser tracker at the same location, tilt the laser tracker by a small amount so that the inclinometer readings change by a small amount.

(g) Establish a new level frame so that the z-axis is once again aligned with the gravity direction.

(h) Repeat steps (b) through (d).

(i) Record the z-coordinates of SMRs located at nests B and C, z_{B2} and z_{C2} , as measured by the laser tracker in the coordinate system established in (d).

(j) Calculate the errors, Δz_B and Δz_C , determined as the difference in the z-coordinates of SMRs located at nests B and C before and after tilting, i.e., $\Delta z_B = z_{B2} - z_{B1}$ and $\Delta z_C = z_{C2} - z_{C1}$.

(k) Convert the errors in z heights to angular units, i.e., $e_B = \Delta z_B / (2d)$ and $e_C = \Delta z_C / (2d)$.

(l) Compare these errors against the MPEs for the inclinometer error in units of angle. The laser tracker has passed the test if $|e_B| < \text{MPE}$ and $|e_C| < \text{MPE}$.

F-5.2.4 Inclinometer Test Based on Tracker Translation. For the second mode of inclinometer usage, there is an additional error source that scales with range to the target. This error source can be detected by measuring the coordinates of SMRs located at nests A and B from within the line AB, and again from outside the line AB, in a manner similar to that adopted for optical levels. However, by moving the tracker from position 1 to position 2 (or vice versa), the test convolves any inclinometer errors with errors in the vertical angle encoder. It should therefore be cautioned that the MPE for the inclinometer test based on tracker translation may be larger than the MPE for the inclinometer test based on tracker tilt (see para. F-5.2.3).

The test procedure is as follows:

(a) Using software provided by the manufacturer or by a third party, establish a level frame so that the z-axis of the laser tracker's coordinate system is aligned with the gravity direction. This requires measurement of the inclinometer followed by coordinate transformation from the laser tracker's base coordinate system to one whose z-axis is aligned with gravity.

(b) Measure the coordinates of SMRs located at nests A, B, and C in the level-frame coordinate system.

(c) Translate the coordinate system so that the origin is located at nest A.

(d) Rotate the coordinate system so that nest B lies on the YZ plane; ensure that the z-axis continues to remain aligned with the gravity direction.

(e) Record the z-coordinates of SMRs located at nests B and C, z_{B1} and z_{C1} , as measured by the tracker in the coordinate system established in (d).

(f) Move the laser tracker to position 2 if it was previously at position 1. If the laser tracker was previously at position 2, move it to position 1.

(g) Establish a new level frame so that the z-axis is once again aligned with the gravity direction.

(h) Repeat steps (b) through (d).

(i) Record the z-coordinates of SMRs located at nests B and C, z_{B3} and z_{C3} , as measured by the laser tracker in the transformed coordinate system.

(j) Calculate the errors, Δz_B and Δz_C , determined as the difference in the z-coordinates of SMRs located at nests B and C, before and after tilting, i.e., $\Delta z_B = z_{B3} - z_{B1}$ and $\Delta z_C = z_{C3} - z_{C1}$.

(k) Convert the errors in z heights to angular units, $e_B = \Delta z_B / (2d)$ and $e_C = \Delta z_C / (2d)$.

(l) Compare these errors against the MPEs in units of angle. The laser tracker has passed the test if $|e_B| < \text{MPE}$ and $|e_C| < \text{MPE}$.

F-5.2.5 Additional Notes. There is an advantage to performing the test described in para. F-5.2.4 for all trackers, regardless of the mode of inclinometer usage. The eccentricity of the vertical angle encoder along the vertical axis is not captured with adequate sensitivity through the tests described in para. F-5.2.3. By taking advantage of the lever arm obtained by moving the tracker from position 1 to position 2, the test in para. F-5.2.4 is considerably more sensitive to vertical angle encoder eccentricity. However, as mentioned earlier, the test convolves this vertical angle encoder eccentricity with the inclinometer errors; thus, the ability to detect vertical angle encoder eccentricity is limited by the accuracy of the inclinometer.

(d) Rotate the coordinate system so that nest B lies on the YZ plane; ensure that the z-axis continues to remain aligned with the gravity direction.

(e) Record the z-coordinates of SMRs located at nests B and C, z_{B1} and z_{C1} , as measured by the tracker in the coordinate system established in (d).

(f) While keeping the laser tracker at the same location, tilt the laser tracker by a small amount so that the inclinometer readings change by a small amount.

(g) Establish a new level frame so that the z-axis is once again aligned with the gravity direction.

(h) Repeat steps (b) through (d).

(i) Record the z-coordinates of SMRs located at nests B and C, z_{B2} and z_{C2} , as measured by the laser tracker in the coordinate system established in (d).

(j) Calculate the errors, Δz_B and Δz_C , determined as the difference in the z-coordinates of SMRs located at nests B and C before and after tilting, i.e., $\Delta z_B = z_{B2} - z_{B1}$ and $\Delta z_C = z_{C2} - z_{C1}$.

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(g) Establish a new level frame so that the z-axis is once again aligned with the gravity direction.

(h) Repeat steps (b) through (d).

(i) Record the z-coordinates of SMRs located at nests B and C, z_{B3} and z_{C3} , as measured by the laser tracker in the transformed coordinate system.

(j) Calculate the errors, Δz_B and Δz_C , determined as the difference in the z-coordinates of SMRs located at nests B and C, before and after tilting, i.e., $\Delta z_B = z_{B3} - z_{B1}$ and $\Delta z_C = z_{C3} - z_{C1}$.

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B89 AMERICAN NATIONAL STANDARDS FOR DIMENSIONAL METROLOGY AND CALIBRATION OF INSTRUMENTS

B89-1990	Space Plate Test Recommendations for Coordinate Measuring Machines (Technical Paper)
B89 Report-1990	Parametric Calibration of Coordinate Measuring Machines (Technical Paper)
B89.1.2M-1991	Calibration of Gage Blocks by Contact Comparison Methods (Through 20 in. and 500 mm)
B89.1.5-1998 (R2019)	Measurement of Plain External Diameters for Use as Master Discs or Cylindrical Plug Gages
B89.1.6-2002 (R2017)	Measurement of Plain Internal Diameters for Use as Master Rings or Ring Gages
B89.1.7-2009 (R2019)	Performance Standard for Steel Measuring Tapes
B89.1.8-2011 (R2021)	Performance Evaluation of Displacement-Measuring Laser Interferometers
B89.1.9-2002 (R2012)	Gage Blocks
B89.1.10M-2001 (R2021)	Dial Indicators (for Linear Measurements)
B89.1.13-2013	Micrometers
B89.1.14-2018	Calipers
B89.1.17-2001 (R2017)	Measurement of Thread Measuring Wires
B89.3.1-1972 (R2003)	Measurement of Out-of-Roundness
B89.3.4-2010 (R2019)	Axes of Rotation: Methods for Specifying and Testing
B89.3.7-2013 (R2018)	Granite Surface Plates
B89.4.1-1997	Methods for Performance Evaluation of Coordinate Measuring Machines
B89.4.10-2021	Methods for Performance Evaluation of Coordinate Measuring System Software
B89.4.19-2021	Performance Evaluation of Laser-Based Spherical Coordinate Measurement Systems
B89.4.21.1-2020	Environmental Effects on Coordinate Measuring Machine Measurements
B89.4.22-2004 (R2019)	Methods for Performance Evaluation of Articulated Arm Coordinate Measuring Machines
B89.4.23-2020	X-Ray Computed Tomography (CT) Performance Evaluation
B89.4.10360.2-2008 (R2012)	Acceptance Test and Reverification Test for Coordinate Measuring Machines (CMMs) – Part 2: CMMs Used for Measuring Linear Dimensions
B89.6.2-1973 (2017)	Temperature and Humidity Environment for Dimensional Measurement
B89.7.1-2016	Guidelines for Addressing Measurement Uncertainty in the Development and Application of ASME B89 Standards (Technical Report)
B89.7.2-2014 (R2019)	Dimensional Measurement Planning
B89.7.3.1-2001 (R2019)	Guidelines for Decision Rules: Considering Measurement Uncertainty in Determining Conformance to Specifications
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