ASME B89.4.19-2006

Performance Evaluation of Laser-Based Spherical Coordinate Measurement Systems

AN AMERICAN NATIONAL STANDARD

The American Society of Mechanical Engineers

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Three Park Avenue • New York, NY 10016

Date of Issuance: November 30, 2006

The next edition of this Standard is scheduled for publication in 2011. There will be no addenda issued to this edition.

ASME issues written replies to inquiries concerning interpretations of technical aspects of this Standard. Interpretations are published on the ASME website under the Committee Pages at http://cstools.asme.org as they are issued.

The American Society of Mechanical Engineers
Three Park Avenue, New York, NY 10016-5990

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FOREWORD

ASME Standards Committee B89 on Dimensional Metrology, under procedures approved by the American National Standards Institute (ANSI), prepares standards that encompass the inspection and the means of measuring characteristics of such various geometric parameters as diameter, length, flatness, parallelism, concentricity, and squareness.

Division B89.4 produces Standards and Technical Reports in the area of coordinate measuring technology, with particular focus on coordinate measuring machines (CMMs). This Standard, addressing the performance evaluation of laser trackers and similar large-scale measurement systems, is the work of the B89.4.19 Project Team on Optical CMM Evaluation.

Performance evaluation of a laser tracker presents challenges different from those associated with conventional Cartesian CMMs. Because of the very large working volume, no full-scale, three-dimensional calibrated artifacts exist, and the design of the laser beam steering system is such that individual parametric errors cannot, in general, be isolated and measured individually. For any coordinate measurement system, a fundamental requirement is a test of its ability to realize the SI unit of length, the meter. In a laser tracker, the length scale is often a laser interferometer and usually one does not have a significantly more accurate reference interferometer with which to perform such a test.

For these reasons, the performance evaluation tests in this Standard consist primarily of point-to-point length measurements using calibrated artifacts that can be realized in a number of ways. Measured lengths are compared with manufacturers Maximum Permissible Error (MPE) specifications in order to decide conformance. Realization of the SI meter can be evaluated in a number of ways, including calibration of the laser interferometer, measurement of a series of short calibrated reference lengths, or measurement of a series of long calibrated reference lengths. Procedures are also included for testing the absolute distance measurement (ADM) capability of laser trackers that include this option.

All reference lengths used in the performance evaluation tests are required to be traceable per ASME B89.7.5. Guidance is provided on how to demonstrate this traceability, as well as the traceability of subsequent point-to-point length measurements made with a laser tracker that has passed the performance evaluation tests of this Standard.

Suggestions for improvement of this Standard are welcome. They should be sent to The American Society of Mechanical Engineers, Secretary, B89 Standards Committee, Three Park Avenue, New York, NY 10016-5990.

This Edition was approved by the American National Standards Institute on January 30, 2006.

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Dimensional Metrology

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General. ASME Standards are developed and maintained with the intent to represent the consensus of concerned interests. As such, users of this Standard may interact with the Committee by requesting interpretations, proposing revisions, and attending Committee meetings. Correspondence should be addressed to:

Secretary, B89 Standards Committee
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Proposing Revisions. Revisions are made periodically to the Standard to incorporate changes that appear necessary or desirable, as demonstrated by the experience gained from the application of the Standard. Approved revisions will be published periodically.

The Committee welcomes proposals for revisions to this Standard. Such proposals should be as specific as possible, citing the paragraph number(s), the proposed wording, and a detailed description of the reasons for the proposal, including any pertinent documentation.

Interpretations. Upon request, the B89 Committee will render an interpretation of any requirement of the Standard. Interpretations can only be rendered in response to a written request sent to the Secretary of the B89 Standards Committee.

The request for interpretation should be clear and unambiguous. It is further recommended that the inquirer submit his/her request in the following format:

Subject:	Cite the applicable paragraph number(s) and the topic of the inquiry.
Edition:	Cite the applicable edition of the Standard for which the interpretation is being requested.
Question:	Phrase the question as a request for an interpretation of a specific requirement suitable for general understanding and use, not as a request for an approval of a proprietary design or situation. The inquirer may also include any plans or drawings, which are necessary to explain the question; however, they should not contain proprietary names or information.

Requests that are not in this format will be rewritten in this format by the Committee prior to being answered, which may inadvertently change the intent of the original request.

ASME procedures provide for reconsideration of any interpretation when or if additional information that might affect an interpretation is available. Further, persons aggrieved by an interpretation may appeal to the cognizant ASME Committee or Subcommittee. ASME does not "approve," "certify," "rate," or "endorse" any item, construction, proprietary device, or activity.

Attending Committee Meetings. The B89 Standards Committee regularly holds meetings, which are open to the public. Persons wishing to attend any meeting should contact the Secretary of the B89 Standards Committee.

PERFORMANCE EVALUATION OF LASER-BASED SPHERICAL COORDINATE MEASUREMENT SYSTEMS

1 SCOPE

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 such instruments 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 an instrument that directs the light from a ranging 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 an instrument 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 focuses specifically on the use of laser trackers as industrial measurement tools rather than their use in surveying or geodesy. Specified tests are designed to evaluate the point-to-point length measurement capabilities of these instruments. 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

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

Instruments that have passed the performance tests of this Standard are considered capable of producing traceable point-to-point length measurements for the stated conditions required in this Standard. 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.

Several appendices describe various factors that should be considered when using this Standard. Appendix I is mandatory, and the remaining Appendices are nonmandatory.

(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 Technical Report.

(b) Nonmandatory Appendix A discusses the traceability of laser tracker point-to-point length measurements performed subsequent to an instrument's passing the performance 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 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.

(e) Nonmandatory Appendix D describes three 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. This Appendix also describes the measurement capability index and a 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

[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.

(1) radial errors due to speed of light variations

(2) angular (or transverse) errors due to beam refraction

A numerical example illustrates the use of the formulae.

(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 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 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. The reference length orientations and instrument positions in the evaluation have been chosen for their sensitivity to characteristic systematic errors known to occur in laser trackers.

Additional tests are included that characterize the consistency of the coordinates of a point when measured in both frontsight and backsight 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 must 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 2.

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 if a particular instrument will be evaluated, including the cost and location of the evaluation. Laser trackers that have successfully passed the performance evaluation, i.e., the instrument's measurement errors are not greater than the corresponding *MPE*s, 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 tests emphasize the use of good metrology practice and simple fixtures. They stress the importance of measurement procedure details, i.e., the measurement data are the result of the complete measuring system including the targets and probes.

3 SPECIFICATIONS AND RATED CONDITIONS

Any manufacturer's specification that conforms to this Standard shall include completed Form 1 (General Specifications and Rated Conditions) and the specifications of Form 2 (Manufacturer's Performance Specifications and Test Results). The manufacturer shall provide a formula for calculating the maximum permissible error (*MPE*) for point-to-point length measurements that is applicable over the entire range of rated conditions as described in Form 1.

4 DEFINITIONS

This section contains brief definitions of technical terms specific to this Standard. All other definitions herein will refer to and comply with the International Vocabulary of Basic and General Terms in Metrology (VIM).[2]

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

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

calibration: set of operations that establish, under specified conditions, the relationship between values of quantities indicated by a measuring instrument or measuring system, or values represented by a material measure or a reference material, and the corresponding values realized by standards (see VIM 6.11).

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

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

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

frontsight/backsight: these are modes of measurement. Frontsight is the normal measurement mode of the instrument. Backsight is obtained by rotating the instrument about the vertical axis by 180 deg and then rotating the beam steering mechanism about the horizontal axis to repoint at the target.

NOTE: Frontsight/backsight are sometimes referred to as direct/reverse and face 1/face 2.

[2] International Organization for Standardization (ISO), 1 rue de Varembé, Case Postale 56, CH-1211, Genève 20, Switzerland/Suisse.

Form 1 General Specifications and Rated Conditions

RATED CONDITIONS

Measurement Envelope

Distance	Min. ______ m	Max. ______ m
Range of horizontal angles		______ deg
Range of vertical angles		______ deg

a. *Temperature Range*

Operating	Min. ______ °C	Max. ______ °C
Thermal gradient limits	Max. ______ °C/m	Max. ______ °C/h

b. *Humidity Range*

Operating	Min. ______ % RH	Max. ______ % RH

c. *Barometric Pressure Range*

Operating	Min. ______ mm Hg	Max. ______ mm Hg

d. *Ambient Light:* The manufacturer shall identify conditions, if any, under which ambient light degrades specifications.

e. *Electrical:* The electrical power supplied to a machine can affect its ability to perform accurate and repeatable measurements. This is particularly true when a machine uses some form of computer for any control or readout function.

Voltage	________ V	Current	________ A
Frequency	________ Hz	Surge/Sag	________ V
Max. transient voltages and duration	________ V		________ s

f. *Probe Type:* The probe diameter and reflector type (e.g., cube corner, glass prism) used during performance testing shall be specified.

Diameter ______ mm Reflector type ____________________

g. *Sampling Strategy:* The manufacturer shall state the measurement acquisition time (averaging time) and sampling frequency (points per second) to meet specification.

Acquisition time ______ s Frequency ________ point/s

LIMITING CONDITIONS

h. *Temperature Range*

Min. ________ °C Max. ________ °C

i. *Humidity Range*

Min. ________ % RH Max. ________ % RH

j. *Barometric Pressure Range*

Min. ________ mm Hg Max. ________ mm Hg

Form 2 Manufacturer's Performance Specifications and Test Results (All Units μm)

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 NOTE:

(a) 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.

(b) 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.

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

NOTE: The home point serves as a distance reference for the laser tracker's ranging devices.

IFM: a laser displacement interferometer internal to a laser tracker, derived from interferometer.

influence quantity: quantity that is not the measurand but that affects the result of the measurement (see VIM 2.7).

limiting conditions: manufacturer's specified limits on the environmental, utility, and other conditions within which an instrument may be operated safely and without damage.

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

maximum permissible error (MPE): extreme values of an error permitted by specification, regulations, etc. for a given measuring instrument (VIM 5.21).

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

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

measurand: particular quantity subject to measurement (VIM 2.6).

measurement capability index: ratio of the *MPE* of a length measurement to the expanded uncertainty of the corresponding reference length.

rated conditions: manufacturer-specified limits on the environmental, utility, and other conditions within which the manufacturer's performance specifications are guaranteed at the time of installation of the instrument.

reference length: 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: 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 temperature, barometric pressure, relative humidity and chemical composition. Its effect must be compensated for when light is used to realize the metric (scale). A detailed discussion is given in Nonmandatory Appendix C.

refractivity (N): related to the refractive index n by: $N = (n-1) \times 10^6$.

retroreflector: passive device that reflects light back 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): 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.

traceability: property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties (see VIM 6.10).

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

two-face test: test that is performed to characterize certain geometric errors of the instrument.

NOTE: Frontsight/backsight measurements are used in the two-face test.

5 TEST ENVIRONMENT

The manufacturer shall specify the rated conditions of section 3. If the user specifies that the performance 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.

6 PERFORMANCE 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 such 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 instrument 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 reverse and are thus 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 meter). Ranging tests are described in para. 6.4.

Table 1 Laser Tracker Performance Evaluation Requirements

Laser Tracker Configuration	System Tests (Paras. 6.2 and 6.3)	Ranging Tests (Para. 6.4)
Interferometer only	All	Interferometer ranging test (para. 6.4.2)
Absolute distance meter (ADM) only	All	ADM ranging test (para. 6.4.3)
Interferometer and ADM	All (using interferometer ranging system)	Interferometer ranging test (para. 6.4.2)
(Default test method)	All (using ADM ranging system)	ADM ranging test (para. 6.4.3)
Interferometer and ADM	Horizontal Length Measurement System Test Position 1 (para. 6.2.4) using IFM ranging system	Interferometer ranging test (para. 6.4.2)
(Alternative test method)	All (using ADM ranging system)	ADM ranging test (para. 6.4.3)

6.1 General Requirements

The supplier shall be responsible for providing a laser tracker that meets the performance specifications of section 3 when the instrument 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, spherically mounted reflectors (SMRs), or other equipment, 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 subsystem(s) as part of the purchase agreement, the supplier will state the subsystem specifications necessary to meet the laser tracker performance specifications of section 3. 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(s) 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 system incorporated in the laser tracker under evaluation. Specifically, instruments with an interferometer (IFM) only, an absolute distance meter (ADM) only, or both an IFM and ADM, require different tests that are sensitive to the unique error sources of these systems.

The specific tests that shall be performed for each laser tracker configuration are shown in Table 1. An instrument 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 rule[3] 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 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,[4] and the expanded uncertainty U of the reference length should not exceed one-fourth the *MPE* for the performance tests specified in para. 6.2 and should not exceed one-half the *MPE* for the performance tests specified in para. 6.4. This corresponds to a measurement capability index $C_m = MPE/U$ equal to 4 and 2, respectively. (See Nonmandatory Appendix D, para. D-2.3 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 at its ends (a scale bar)

[3] Refer to ASME B89.7.3.1-2001, para. 4.1.

[4] 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.

(b) two retroreflector target nests mounted on independent freestanding rigid structures, with the distance between the nests measured by a distance or displacement measuring device

(c) a reference length created by a rail and carriage system used in combination with an integrally mounted distance or displacement measuring device

Guidance for realizing a reference length by one of these three methods is discussed in Nonmandatory Appendix D, including a discussion of evaluating the uncertainty in the realized length.

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 measuring envelope. It should be noted that the setups shown in the illustrations to Tables 2, 3, 4, and 5 show a reference length realized using two retroreflector target nests as described in para. 6.2.1(b). If using a scale bar or laser rail, modified setups will be required.

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.

When measuring a reference length, the SMR/target should be positioned in approximately the same orientation relative to the measurement beam. This procedure minimizes the influence of geometric errors in the construction of the SMR/target on the length measurement system tests. (For information on SMR testing see Nonmandatory Appendix B.) It is recommended that a single SMR/target be employed to perform all of the tests described in this Standard. 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.

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 than 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.

Alternatively, if the reference length is realized using freestanding structures or a rail/carriage system, the environmental conditions must be monitored in order to correct for changes in the refractive index of air. Details for performing this calculation are given in Nonmandatory Appendix C. Typically, the software provided with commercially available displacement measuring interferometers provides a utility for performing this calculation and automatically compensating the laser wavelength.

6.2.3 Failure to Satisfy *MPE* Requirements. If, during the course of testing, a test measurement fails to conform to the corresponding *MPE* requirement and the environment satisfies the requirements of section 3, then the following actions shall be taken:

Step 1: Examine the reference length to assess its stability and if necessary recalibrate the reference length. 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 magnitude of the largest error (measured length minus reference length) to replace the failed position value.

Step 3: If the new value satisfies the *MPE* requirement then the laser tracker satisfies the requirements for that measurement 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 fails the *MPE* for the measurement, it fails the performance test. The instrument shall be repaired or replaced and the performance testing begun anew.

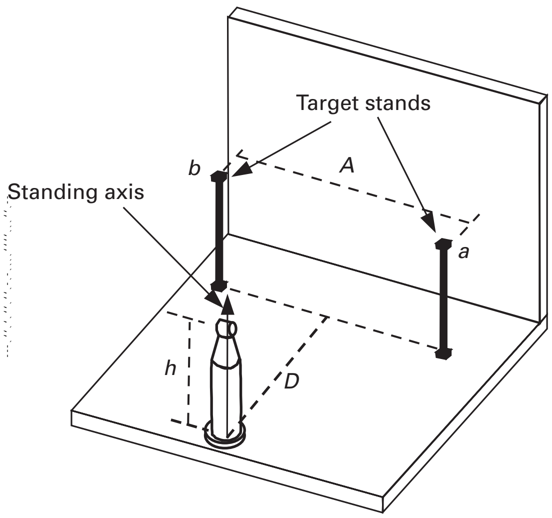
NOTE: The five repeated measurements are required to replace one measurement result; three repeated measurements are still required for each test position.

6.2.4 Horizontal Length Measurement System Tests. A horizontal reference length having endpoints *a* and *b* is set up as shown in illustration to Table 2. 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 the targets at points *a* and *b*. *D* represents the distance between the reference length and the laser tracker. Additionally, the instrument shall be positioned so that it is approximately equidistant from target nests *a* and *b*. Measurements are made with the laser tracker positioned and oriented as described in Table 2.

The specified horizontal angles represent physical rotations of the laser tracker about the standing axis. The full range of specified horizontal angles may not be possible for the laser tracker under test. In this case, measurements shall be evenly spaced and equally distributed within the available angular range.

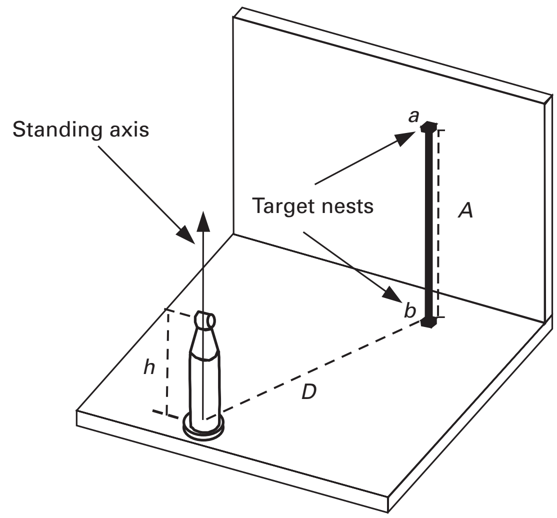
Three measurements are performed in each position. The measurement results shall be reported as described in section 7.

Table 2 Horizontal Length Measurement System Test



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

Table 3 Vertical Length Measurement System Test



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

6.2.5 Vertical Length Measurement System Tests. A vertical reference length having endpoints *a* and *b* is set up as shown in the illustration to Table 3. The length *A* should be at least 2.3 m. The height *h* of the laser tracker should be approximately midway between the heights of points *a* and *b*. *D* represents the distance between the reference length and the laser tracker. Measurements are made with the instrument positioned and oriented as described in Table 3.

The specified horizontal angles represent physical rotations of the laser tracker about the standing axis. The full range of specified horizontal angles may not be possible for the laser tracker under test. In this case, measurements shall be evenly spaced and equally distributed within the available angular range.

Three measurements are performed in each position. The measurement results shall be reported as described in section 7.

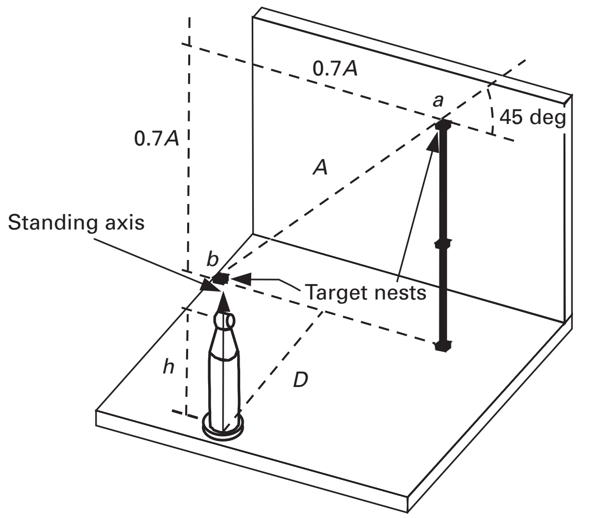
6.2.6 Right Diagonal Length Measurement System Tests. A right diagonal reference length having endpoints *a* and *b* is set up as shown in the illustration to Table 4. The length *A* should be at least 2.3 m. The height *h* of the laser tracker should be approximately midway between the heights of points *a* and *b*. *D* represents the distance between the reference length and the laser tracker. Additionally, the instrument shall be positioned so that it is approximately equidistant from target nests *a* and *b*. Measurements are made with the laser tracker positioned and oriented as described in Table 4.

The specified horizontal angles represent physical rotations of the laser tracker about the standing axis. The full range of specified horizontal angles may not be possible for the laser tracker under test. In this case, measurements shall be evenly spaced and equally distributed within the available angular range.

Three measurements are performed in each position. The measurement results shall be reported as described in section 7.

6.2.7 Left Diagonal Length Measurement System Tests. A left diagonal reference length having endpoints *a* and *b* is set up as shown in the illustration to Table 5. The length *A* should be at least 2.3 m. The height

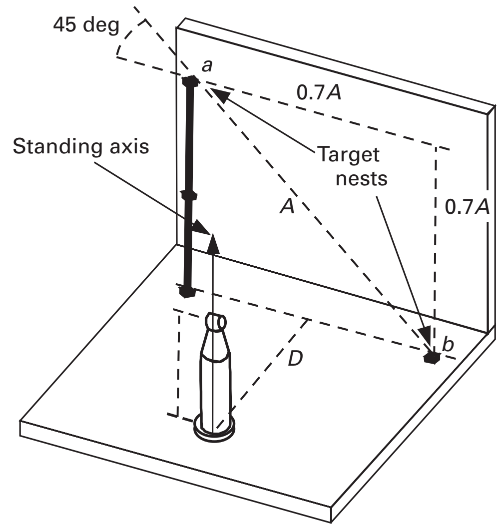
Table 4 Right Diagonal Length Measurement System Test



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

GENERAL NOTE: The lengths and angles are approximate.

Table 5 Left Diagonal Length Measurement System Test



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

GENERAL NOTE: The lengths and angles are approximate.

h of the laser tracker should be approximately midway between the heights of points *a* and *b*. *D* represents the physical distance between the reference length and the laser tracker. Additionally, the instrument shall be positioned so that it is approximately equidistant from target nests *a* and *b*. Measurements are made with the laser tracker positioned and oriented as described in Table 5.

The specified horizontal angles represent physical rotations of the laser tracker about the standing axis. The full range of specified horizontal angles may not be possible for the laser tracker under test. In this case, measurements shall be evenly spaced and equally distributed within the available angular range.

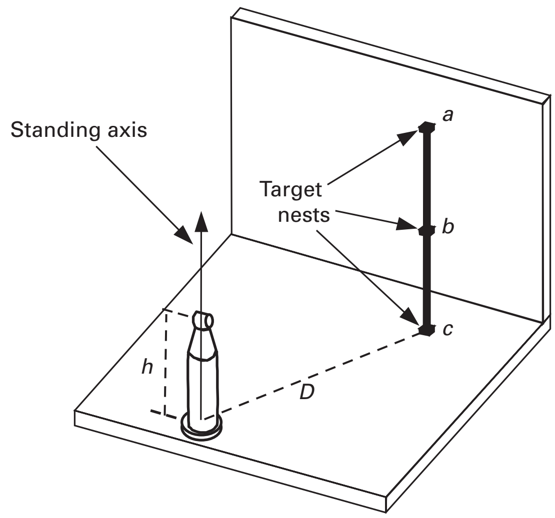
Three repeated measurements are performed in each position. The measurement results shall be reported as described in section 7.

6.2.8 User-Selected Length Measurement System Tests. The user shall specify two additional length measurements anywhere in the laser tracker measurement envelope. The following two positions are the recommended default test positions that will be used in the event that the user does not explicitly specify additional positions. Each of the two positions shall be measured three times and the measurement results shall be reported as described in section 7.

(a) The first default position is strongly recommended for users that measure extensively in the vertical direction, i.e., this position emphasizes the vertical angle encoder of the laser tracker. The test position is similar to that of the illustration in Table 3, except that the reference length is shifted vertically such that the lower target nest (denoted as *b* in illustration in Table 3) is approximately at the laser tracker height. The instrument should be as close as possible to the reference length (i.e., the distance *D* in illustration in Table 3 should be minimized) while still allowing the upper target nest to be measured (i.e., target nest *a* must be within the measurement range of the vertical angle encoder of the laser tracker).

(b) The second default position is similar to that of para. 6.2.6 but the reference length is positioned at a compound angle that involves approximately the same

Table 6 Two-Face System Test Measurement



Position Number	Distance, *D* (Approximate)	Measured Horizontal Angle to Target *b*, deg
1	Note (1)	0
2	Note (1)	90
3	Note (1)	180
4	Note (1)	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

NOTE:
(1) Minimize *D* in order to maximize the vertical angular range of motion between nests *a* and *c*.

displacement for all three laser tracker axes (radial and both angular axes). The center of the reference length shall be approximately at the laser tracker's height and 5 m from the instrument.

The user may specify positions other than the default positions. However, if the specified positions require a reference length other than the length(s) used for testing in paras. 6.2.4 through 6.2.7 and para. 6.3, then the user is responsible for providing the traceable reference lengths for these measurements. Metrological traceability of the reference length shall be established as described in Mandatory Appendix I.

6.3 Two-Face System Tests

6.3.1 Two-Face Test Procedure. The two-face measurement setup is shown in the illustration in Table 6. Three target nests are placed as shown: one on the floor, one at approximately laser tracker height, and one at twice the laser tracker height above the floor. *D* represents the distance between the instrument and the target nest on the floor. Measurements are made with the laser tracker positioned as described in Table 6.

The specified horizontal angles represent physical rotations of the laser tracker about the standing axis. The full range of specified horizontal angles may not be possible for the instrument under test. In this case, measurements shall be evenly spaced and equally distributed within the available angular range. Measurements are performed by first recording the coordinates of the target in frontsight mode. The target coordinates are then recorded in backsight mode. This procedure is repeated a total of three times at each target location. Measurement results are reported as described in section 7.

6.3.2 Failure to Satisfy *MPE* Requirements. If, during the course of testing, a test measurement fails to conform to the corresponding *MPE* requirement and the environment satisfies the requirements of section 3, then the following actions shall be taken:

Step 1: Examine the target nest to assess its stability and if necessary clean and secure the nest and its stand.

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

Step 3: If the new value satisfies the *MPE* requirement, then the laser tracker satisfies the requirements for that measurement 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 no more than twice) and if the laser tracker still fails the *MPE* for the measurement, it fails the performance test. The instrument shall be repaired or replaced and the performance testing begun anew.

NOTE: The five repeated measurements are required to replace one measurement result; three repeated measurements are still required for each test position.

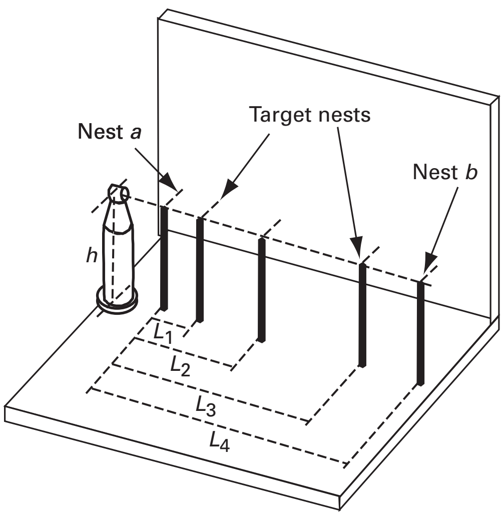
6.4 Ranging Tests

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

(a) Long Reference Lengths [see paras. 6.4.2(a) and 6.4.4(a) and (b)]

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

Table 7 Ranging Test



Position Number	Reference Lengths [Note (1)]	Measured Zenith Angle to Target Nest *a* and *b*, deg
1	$L_1 \approx 18\%R$	90
2	$L_2 \approx 36\%R$	90
3	$L_3 \approx 54\%R$	90
4	$L_4 \approx 72\%R$	90
5	User selected	90
6	User selected	90

NOTE:
(1) R = maximum ranging distance.

where L_{ref} is the reference length as appropriate from Table 7. (Also see Nonmandatory Appendix D, para. D-2.3.)

(b) Short Reference Lengths [see para. 6.4.2(b)]

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

where L_{ref} is the short reference length from para. 6.4.2.(b)

(c) Laser Interferometer Calibration [see para. 6.4.2(c)]

$$C_m = \frac{(MPE)(L_{ref})}{U_{k\,=\,2}(L_{ref})} \geq 2$$

where L_{ref} is the reference length as appropriate from Table 7 and $U_{k\,=\,2}(L_{ref})$ is evaluated as in Appendix D, para. D-3.1. (Also, see para. 7.3 and Mandatory Appendix I.)

Because of the high accuracy (low *MPE*) of some ranging systems, the measurement capability index requirement may not be obtainable. In this case the actual value of C_m for the ranging tests shall be clearly stated on Form 2, and the "Low C_m" box checked. In no case shall C_m be less than 1.

6.4.1.1 Failure to Satisfy *MPE* Requirements. If, during the course of testing, a test measurement fails to conform to the corresponding *MPE* requirement and the environment satisfies the requirements of section 3, then the following actions shall be taken:

In the case of a long or short reference length,

Step 1: Examine the reference length to assess its stability and if necessary recalibrate the reference length. This is particularly relevant to paras. 6.4.2(a) and 6.4.4(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 magnitude of the largest error (measured length minus reference length) to replace the failed position value.

Step 3: If the new value satisfies the *MPE* requirement then the laser tracker satisfies the requirements for that measurement 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 no more than twice) and if the laser tracker still fails the *MPE* for the measurement, it fails the performance test. The instrument shall be repaired or replaced and the performance testing begun anew.

NOTE: In the case of both the long and short reference lengths of para. 6.4.2, the five repeated measurements are required to replace one measurement result; three repeated measurements are still required for each test position.

In the case of a laser calibration of para. 6.4.2, failure to satisfy the *MPE* requirements using this method indicates that the laser interferometer is not operating correctly or the calibration is in doubt, the manufacturer shall address the situation as appropriate.

6.4.2 Interferometer (IFM) Ranging Tests. Laser displacement interferometry is a mature technology that is well understood. IFM testing is focused on length dependent errors, that typically scale linearly with increasing length, and on proper counting of the interferometric fringes. Accordingly, there are three alternative methods that are sufficient to ensure proper operation. The IFM may be tested by any of the following methods:

(a) Long Reference Lengths. The most direct method of testing the IFM ranging capability involves the measurement of four long reference lengths aligned in a pure radial orientation that span a significant portion of the maximum ranging distance. The reference lengths are specified in Table 7, where R taken as the maximum range of the IFM. No user-selected positions are required for the IFM ranging test. Details regarding realizing the

reference lengths are given in para. 6.4.4. Measurement results are reported as described in section 7.

(b) Short Reference Lengths. The laser tracker is set up to perform a pure radial point-to-point length measurement at approximately the laser tracker height. A set of four reference lengths shall be measured. By default, a set of reference lengths approximately equal to 0.5 m, 1.0 m, 1.5 m, and 2.3 m can be used. In no case shall the longest length be less than 1.5 m. Each of the four lengths shall be measured, and then the measurement sequence is repeated two more times for a total of twelve length measurements, i.e., each length is measured three times. Measurement results are reported as described in section 7.

(c) Laser Interferometer Calibration. The interferometer in the laser tracker shall be calibrated according to Draft Standard ASME B89.1.8. From that calibration report, the length dependent error, *LDE*, and the drift value, *D*, shall be reported as described in section 7.

6.4.3 Absolute Distance Meter (ADM) Ranging Tests. The procedures described in this section are designed to test the measurement capability of the ADM ranging system of a suitably equipped laser tracker. This is accomplished by comparing a set of six point-to-point lengths as measured by the ADM with a corresponding set of long reference lengths aligned in a pure radial orientation that span a significant portion of the maximum ranging distance. The reference lengths are specified in Table 7, where *R* taken as the maximum range of the ADM, including two user-selected lengths. Details regarding realizing the reference lengths are given in para. 6.4.4. Measurement results are reported as described in section 7.

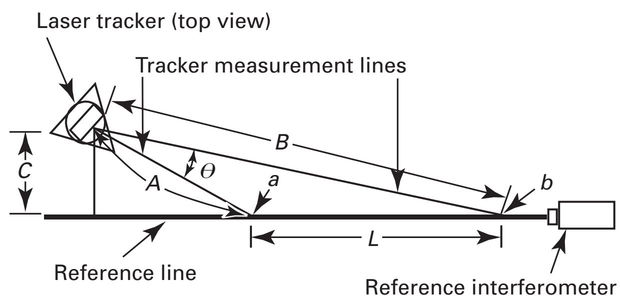
NOTE: The method used to test the IFM and ADM ranging systems are not required to be the same. For example, the IFM might be tested using the laser calibration procedure [para. 6.4.2(c)], while the ADM might be tested using a laser rail calibrated with the IFM (assuming the IFM met the requirements of para. 6.4.2 and the measurement capability index).

6.4.4 Long Reference Lengths for Ranging Tests. Long reference lengths may be realized by either of the following methods:

(a) Lengths Created Using Rail (Typically Longer Than 20 m) and Target Carriage Whose Motion Is Measured With Displacement Interferometer. In the case of ADM ranging tests, if the laser tracker has an internally mounted laser interferometer (IFM) that meets the requirements of para. 6.4.2 and the measurement capability index requirements, the laser tracker may be used to calibrate the ADM reference lengths along the rail.

(b) Retroreflector Target Nests Mounted on Independent Freestanding Rigid Structures With Distance Between Nests Calibrated by Suitable Technique, e.g., Laser Displacement Interferometer. Again, for the ADM ranging tests, if the laser tracker has an IFM that meets the requirements

Fig. 1 Laser Tracker and Reference Interferometer Alignment



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

of para. 6.4.2, then this interferometer may be used to calibrate the reference lengths.

The reference lengths are denoted L_1 through L_4 in the illustration in Table 7. As depicted in the illustration, a reference length is the length between the target nest closest to the laser tracker, nest *a*, and each of the subsequent target nests. Target nest *a* should be placed at 3 m from the laser tracker. The nests collinear with those labeled *a* and *b* shall be along the radial direction of the laser tracker at approximately the height, *h*, of the instrument.

A single measurement consists of measuring the distance to each of the target nests in sequence, from furthest to nearest. These distances are then used to calculate the lengths depicted in the illustration in Table 7. Three measurements of each reference length shall be performed, and the results shall be reported as described in section 7.

Care should be taken to provide a thermal environment for the laser beam path in compliance with the manufacturer's specifications (see Nonmandatory Appendix E). Measurements are made with the laser tracker positioned and oriented as described in Table 7.

For the case of ADM range testing, the user shall specify two additional length measurements by selecting two additional target locations along the radial line connecting nests *a* and *b*. The user-selected lengths are then the lengths between target nest *a* and the two user-selected target positions.

6.4.4.1 Cosine Error. The laser tracker beam path should be sufficiently aligned along the reference length so that the cosine error is negligible during the range testing. The magnitude of the cosine error can be calculated by reference to Fig. 1.

Lengths *A* and *B* in Fig. 1 represent the laser tracker range measurements to points labeled *a* and *b*. The reference length is depicted by line segment *L* joining the measurement points a and b. The length measurement is given by $B - A$. The cosine error is then

$$\Delta L = (B - A) - L \tag{1}$$

The misalignment of the laser tracker can be determined by either measuring the physical offset of the instrument from the reference line, labeled C in Fig. 1, or by recording the change in angle θ between the two measurement points that comprise a measured length. The angle θ may not lie solely in the horizontal or vertical plane. For the tests described in this Standard, laser tracker pointing is nominally in a horizontal plane. In this case, θ can be estimated by

$$\theta = \sqrt{\Delta H^2 + \Delta V^2} \tag{2}$$

where ΔH and ΔV are the changes, in radians, in the horizontal and vertical angles between the two points that define a reference length.

Once nominal values for the lengths A and B are known, the cosine error ΔL can be calculated given either the offset C or the angle θ, using one of the following equations:

$$\Delta L = (B - A) - \sqrt{B^2 - C^2} - \sqrt{A^2 - C^2} \tag{3}$$

$$\Delta L = (B - A) - \sqrt{(A \sin \theta)^2 + (B - A \cos \theta)^2} \tag{4}$$

Figure 2 shows the cosine error versus offset C for $A = 3$ m and $B = 6$ m, these values are typically the shortest that might be encountered in ranging tests. For larger values of A and B the cosine error rapidly decreases in magnitude. It can be seen, e.g., that an offset $C = 6$ mm results in a cosine error of about 3 μm. This is a small, but not negligible, error when testing high-accuracy ranging systems.

7 ANALYSIS OF PERFORMANCE EVALUATION TESTS

7.1 Evaluation of Length Measurement System Tests of Para. 6.2

The length measuring system tests are evaluated by calculating the magnitude of the difference between the measured length and the reference length using eq. (5).

$$\delta = |L_m - L_{\mathrm{ref}}| \tag{5}$$

where

L_m = length measured by the laser tracker
L_{ref} = reference length

There are three values (δ_1, δ_2, 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 $\delta_{\max} = \max(\delta_1, \delta_2, \delta_3)$ with the corresponding *MPE* specification for that length, i.e., $\delta_{\max} \leq MPE$ for all lengths; see the examples in para. 7.4. Some test positions differ only in the orientation of the laser tracker, e.g., horizontal system test positions 2, 3, 4, and 5 (see Table 2). For a group of test positions a single *MPE* specification is specified and the largest value of $\delta_{\max}$ is reported on Form 2; see example as shown in Form 3.

7.2 Evaluation of Two-Face System Tests of Para. 6.3

The two-face system tests are evaluated by calculating the apparent separation of the measured frontsight and backsight target positions. For each sampled location, the measured target position in frontsight mode is a point P_F with coordinates (x_F, y_F, z_F). In backsight mode, the measured position is a point P_B with coordinates (x_B, y_B, z_B). The distance between these points is the apparent separation Δ as calculated by the laser tracker software. There are three separations (Δ_1, Δ_2, Δ_3) for each test position corresponding to the three repeated measurements. The test of conformance for each location measured in a two-face test requires comparing the largest value $\Delta_{\max} = \max(\Delta_1, \Delta_2, \Delta_3)$ with the corresponding *MPE* specification, i.e., $\Delta_{\max} \leq MPE$ for all lengths; see the examples in para. 7.4. The two-face system tests are combined together in groups differing only in the orientation of the laser tracker, e.g., positions system test positions 1, 2, 3, and 4 (see Table 6). For a group of test positions, a single *MPE* specification is specified, and the largest value of $\delta_{\max}$ is reported on Form 2; see example shown in Form 3.

7.3 Evaluation of Ranging Tests of Para. 6.4

7.3.1 Evaluation of IFM Ranging Tests. For the case of long reference lengths, the ranging test results are evaluated by calculating the magnitude of the difference between the measured length and the reference length using eq. (6).

$$\delta = |L_m - L_{\mathrm{ref}}| \tag{6}$$

where

L_m = length measured by the laser tracker
L_{ref} = reference length

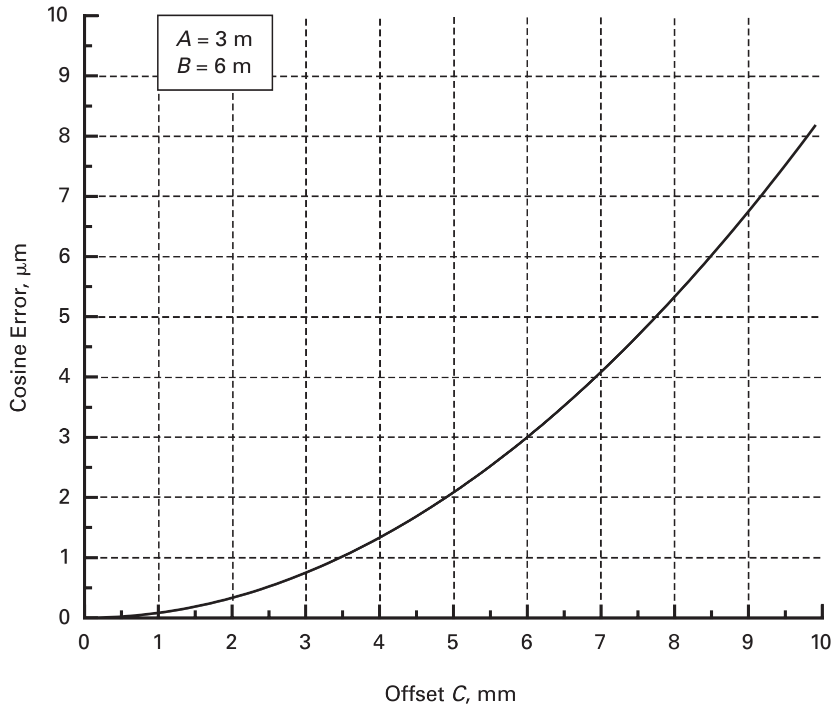
The test of conformance for each measured point-to-point length error requires comparing the value of δ with the corresponding *MPE* specification for that length, i.e., $\delta \leq MPE$ for all lengths δ; see the example in Form 3.

For the case of short reference lengths, the magnitude of the difference between the measured length and the short reference length shall be computed using eq. (7)

$$\varepsilon = |L_m - L_{\mathrm{ref\text{-}short}}| \tag{7}$$

for each of the 12 measured short reference lengths. A least squares line fit shall be performed through all 12 values of ε and the corresponding slope and intercept shall be determined, i.e., $A + B \times L$, where A and B are

Fig. 2 Cosine Error Versus Offset *C* From Reference Line



GENERAL NOTE: In this example, $A = 3$ m and $B = 6$ m (see Fig. 1.).

computed from the least squares fit, see Fig. 3. Four values of δ are computed by using the following equation:

$$\delta = A + B \times L_{ref}$$

where L_{ref} are the four long reference lengths specified in Table 7. The test of conformance for each computed length error requires comparing the value δ with the corresponding *MPE* specification for that length, i.e., $\delta(L_{ref}) \leq MPE$ for all four long lengths given in Table 7; see the examples in para. 7.4.

For the case of the laser interferometer calibration method, four values of δ are computed by the following equation:

$$\delta = D + LDE \times L_{ref}$$

where L_{ref} are the four lengths specified in Table 7 and *D* and *LDE* are the drift value and the length dependent error as reported on the calibration certificate. The test of conformance for each computed length error requires comparing the value δ with the corresponding *MPE* specification for that length, i.e., $\delta(L_{ref}) \leq MPE$ for all four lengths given in Table 7; see the examples in para. 7.4.

7.3.2 Evaluation of ADM Ranging Tests. For the measured long reference lengths, the ranging test results are evaluated by calculating the magnitude of the difference between the measured length and the reference length using eq. (8).

$$\delta = |L_m - L_{ref}| \tag{8}$$

where
L_m = length measured by the laser tracker
L_{ref} = reference length

The test of conformance for each measured point-to-point length error requires comparing the value of δ with the corresponding *MPE* specification for that length, i.e., $\delta \leq MPE$ for all lengths δ; see the examples in para. 7.4.

7.4 Evaluation of Performance Tests

If the value of any length difference δ or any apparent separation Δ is greater than the specified *MPE* for the particular test, the laser tracker fails to meet the manufacturer's performance specification for that measurement. In this case, the procedure of para. 6.2.3, 6.3.2, or 6.4.1.1, as appropriate, shall be followed, and if the instrument still fails to meet the manufacturer's performance specifications, then it will be repaired or replaced before the performance testing is resumed.

7.4.1 Example of Default Test Method. The manufacturer's *MPE*(s) and a set of performance test results for a laser tracker with an ADM and integrally mounted

Form 3 Example of Default Test Method for Manufacturer's Performance Specifications and Test Results (All Units μm)

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 [Note (3)	Y			
IFM Ranging Ref L (2) = 18 m	40	31 [Note (3)	Y			
IFM Ranging Ref L (3) = 27 m	60	48 [Note (3)	Y			
IFM Ranging Ref L (4) = 36 m	80	61 [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 3/18/2005 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 NOTE:

(a) 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.

(b) If an ADM result is used in place of an IFM result, the value should be placed in parentheses.

NOTES:

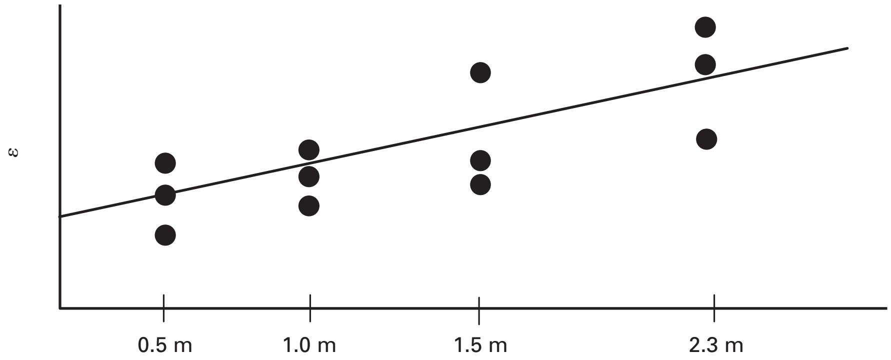
(1) δ for length system results, Δ for two-face results; see paras. 7.1 and 7.2.

(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.

Fig. 3 Least Squares Line Fit to 12 Short Reference Lengths



GENERAL NOTES:
(a) Least squares line fit given by $A + B \times L$.
(b) The fitting determines the values of A and B for the equation of the line.

IFM using the default test method from Table 1 are shown in Form 3.

In Form 3, the maximum errors in positions 5, 6, 7, or 8 for the vertical length measurement system test and position 2, 3, 4, or 5 for the horizontal length measurement system tests exceed the *MPE*(s) for the IFM and ADM systems, respectively. As a consequence, the laser tracker fails to meet the manufacturer's performance specifications.

7.4.2 Example of Alternative Test Method. The alternative test method as described in Table 1 for a laser tracker evaluation with an ADM and integrally mounted interferometer is shown in Form 4. The manufacturer's *MPE*(s) are shown together with the measurement results from the ADM and the required IFM measurements.

Note that the ADM measurements are used in place of the IFM measurements for all of the length measurements except for the first horizontal position. That is, the ADM measurements are used as surrogates for the IFM measurements, except for the horizontal position. This has the advantage of reducing the total number of measurements. The disadvantage is that the ADM errors are typically larger than the corresponding IFM errors, and hence the alternative test method may fail an IFM that would otherwise pass using the default method. If this occurs, it is recommended to perform IFM measurements at the failed positions to determine if the IFM can pass the test.

In Form 4, the maximum errors in position 5, 6, 7, or 8 for the vertical length measurement system test and position 2, 3, 4, or 5 for the horizontal length measurement system tests exceed the *MPE*(s) for the IFM and ADM systems respectively. As a consequence, the instrument fails to meet the manufacturer's performance specifications.

8 REFERENCES

The following is a list of publications referenced in this Standard.

ANSI/NCSL Z540.1-1994 (R2002)
Publisher: National Conference of Standards Laboratories (NCSL) International, 2995 Wilderness Place, Boulder, CO 80301-5404

ASME B89.1.8, Draft Standard
ASME B89.6.2-1973 (R2003), Temperature and Humidity Environment for Dimensional Measurement
ASME B89.7.3.1-2001, Guidelines for Decision Rules: Considering Measurement Uncertainty in Determining Conformance to Specifications
ASME B89.7.5-2006, Metrological Traceability of Dimensional Measurements to the SI Unit of Length (Technical Report)
Publisher: The American Society of Mechanical Engineers (ASME), Three Park Avenue, New York, NY 10016-5990; Order Department: 22 Law Drive, P.O. Box 2300, Fairfield, NJ 07007-2300

International Vocabulary of Basic and General Terms in Metrology, 1993 (VIM)
Publisher: International Organization for Standardization (ISO), 1 rue de Varembé, Case Postale 56, CH-1211, Genève 20, Switzerland/Suisse

Form 4 Example of Alternative Test Method for Manufacturer's Performance Specifications and Test Results (All Units μm)

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	4.8	Y
Horizontal (2, 3, 4, 5)	40	(46.5)	N	43	46.5	N
Horizontal (6, 7, 8, 9)	90	(55.1)	Y	100	55.1	Y
Vertical (1, 2, 3, 4)	40	(10.2)	Y	43	10.2	Y
Vertical (5, 6, 7, 8)	90	(95.2)	N	100	95.2	Y
Right Diagonal (1, 2, 3, 4)	40	(36.2)	Y	43	36.2	Y
Right Diagonal (5, 6, 7, 8)	90	(72.2)	Y	100	72.2	Y
Left Diagonal (1, 2, 3, 4)	40	(35.3)	Y	43	35.3	Y
Left Diagonal (5, 6, 7, 8)	90	(78.2)	Y	100	78.2	Y
User Selected (1)	50	(43.2)	Y	53	43.2	Y
User Selected (2)	15	(4.3)	Y	18	4.3	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 [Note (3)]	Y			
IFM Ranging Ref *L* (2) = 18 m	40	31 [Note (3)]	Y			
IFM Ranging Ref *L* (3) = 27 m	60	48 [Note (3)]	Y			
IFM Ranging Ref *L* (4) = 36 m	80	61 [Note (3)]	Y			
ADM Ranging Ref *L* (1) = 9 m				25	13.5	Y
ADM Ranging Ref *L* (2) = 18 m				50	41.2	Y
ADM Ranging Ref *L* (3) = 27 m				75	69.5	Y
ADM Ranging Ref *L* (4) = 36 m				100	80.5	Y
ADM Ranging Ref *L* User (1) = 22 m				23	15.2	Y
ADM Ranging Ref *L* User (2) = 30 m				25	22.1	Y
Formula for calculating the MPE or attach MPE specification sheet [Note (4)]	See attached specifications.			See attached specifications.		

Test Performed by: Jones Date 3/18/2005 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:

(a) 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.

(b) 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.

MANDATORY APPENDIX I
REFERENCE LENGTH TRACEABILITY

I-1 GENERAL TRACEABILITY ISSUES

This Standard employs the interpretation of traceability described in Technical Report 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 instrument meets the manufacturer's specifications, the reference lengths must satisfy the traceability requirements of section I-2. This provides the connection back to the SI meter and allows a comparison of the measured length errors with the specified *MPE* values.

One of the traceability requirements is for documentation traceability. This is a requirement to describe how the connection to the SI 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, then this interferometer 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 the 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. A calibrated scale bar, e.g., 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 employed will satisfy the traceability requirements for the reference lengths. Information on evaluating the uncertainty of the reference length is given in Nonmandatory Appendix D.

(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. It may be convenient, however, for measurement uncertainty considerations, to perform the calibration at a temperature other than 20°C.

(b) Identify the measurement system or standard used; for example a 2.3 m scale bar made of steel, SN # 12345.

(c) State the expanded ($k = 2$) uncertainty associated with the reference length as used at the time of measurement. This includes effects such as the prevailing thermal conditions at the time the reference length is measured by the laser tracker.

(d) Provide an uncertainty budget describing the uncertainty components used to compute the statement of uncertainty. For a scale bar, the typical uncertainty components are the calibration uncertainty, the uncertainty in the bar temperature (used to make the nominal thermal expansion correction) and the uncertainty in the coefficient of thermal expansion of the bar. Additional uncertainty components may include fixturing effects.

(e) Provide documentation traceability back to an appropriate terminus of the standard used for the reference length; see section I-3 for an appropriate metrological terminus. For example, for a scale bar the calibration certificate would suffice assuming the certificate is from 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; to ensure that other sensors, e.g., the weather station of a reference interferometer is periodically recalibrated; to ensure that the artifact fixturing or other effects are in accordance with its calibration requirements or otherwise taken into account 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 report[1] from a National Measurement Institute for the reference length (artifact or instrument) used as in the testing.

[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.

(b) calibration report from a competent[2] laboratory fulfilling section 5.6 of ISO 17025, or section 9 of ANSI/NCSL Z540.11, for the reference length used in the testing.

(c) documentation describing an independent realization of the SI meter[3] 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., participation in a round robin or comparison against another independently calibrated length standard.

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

[3] In this Standard, an independent realization of the SI meter is considered a reproducible physical phenomenon that has its metrological characteristic (and reproducibility) measured and documented by a NMI. 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

Table A-1 Example Uncertainty Budget

Input Quantity	Standard Uncertainty
Laser tracker	(10 μm + 10 L μm) × 0.58 = 5.8 μm + 5.8 L μm
Temperature	0.5°C × (22 × 10^{-6}/ °C) × L × 0.58 μm = 0 μm + 6.4 L μm
CTE	(2 × 10^{-6}/°C) × L × 10°C) × 0.58 μm = 0 μm + 11.6 L μm
Combined standard uncertainty	5.8 μm + 14.5 L μm
Expanded (k = 2) uncertainty	11.6 μm + 29.0 L μm

This Appendix provides some information on the traceability of subsequent measurements of the laser tracker after a completion of a ASME B89.4.19 performance evaluation. The following example is intended to illustrate a typical scenario:

EXAMPLE: Suppose a user has a laser tracker that has successfully passed a ASME B89.4.19 evaluation, i.e., all of the measured errors were no greater than the manufacturer's corresponding 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 that varies from 20°C to 30°C.

Since there is a large number of various length workpieces 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.

(a) State the measurand; for example, 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) Identify the measurement system or standard used; for example laser tracker #789.

(c) A statement of the expanded (k = 2) uncertainty associated with the result of the measurement; e.g., U = 11.6 μm + 29.0 L μm, where L is in meters (the statement can be in any form, e.g., a table, a formula, produced by software, etc.).

(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 SMR errors (see Nonmandatory Appendix B).

EXAMPLE: Suppose the manufacturer states that the largest point-to-point length error, i.e., the *MPE* (regardless of direction) is 10 μm ± 10 L μm, where L is the nominal length in meters. Further suppose that the temperature is measured with a maximum error of 0.5°C, the *CTE* is (22 ± 2) × 10^{-6} °C^{-1} and that other uncertainty components are negligible.

If uniform probability distributions are assigned to all input quantities, then the required standard uncertainties are just the maximum errors multiplied by $(1/\sqrt{3}\,) \approx 0.58$. The uncertainty budget for this example is illustrated in Table A-1.

(e) Documentation Traceability. There are several possibilities depending on the circumstances of the manufacturer; two examples are listed below.

EXAMPLES:

(1) If the laser tracker manufacturer is ISO 17025 accredited to perform the B89.4.19 testing procedure, then the certificate of a successful performance evaluation, bearing the logo of the accreditation agency, is sufficient evidence of documentation traceability.

(2) If the laser tracker manufacturer is ISO 17025 accredited to perform the B89.1.8 laser interferometer calibration, and the laser interferometer of the laser tracker is so calibrated and used to generate the reference lengths for the performance evaluation, then the completion of a successful performance evaluation and the calibration report of the laser tracker's interferometer, bearing the logo of the accreditation agency, is sufficient evidence of documentation traceability.

(f) An internal quality assurance program is employed by the user that ensures that the laser tracker is periodically recalibrated, that the users are trained to operate the laser tracker in a manner that can realize its specified performance, and that measurements are performed within the stated conditions, e.g., from 20°C to 30°C.

NONMANDATORY APPENDIX B
SPHERICALLY MOUNTED RETROREFLECTOR (SMR) TESTS

B-1 INTRODUCTION

Three types of laser tracker measurement errors are attributable to SMRs containing 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

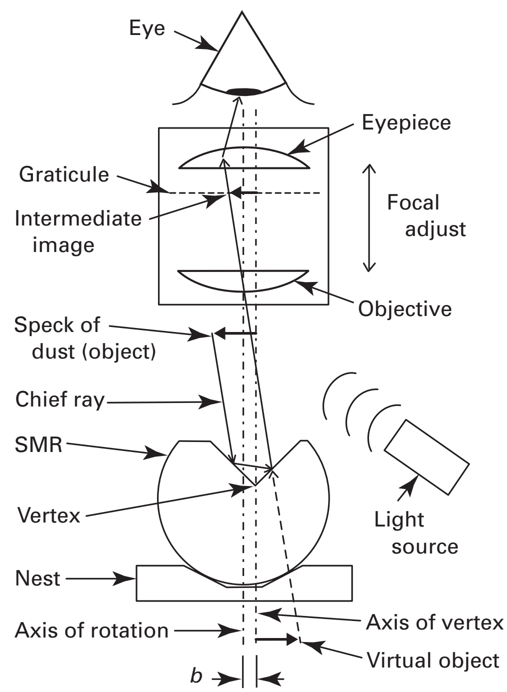
B-2.1 Lateral Centering

As shown in Fig. B-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 Fig. B-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 consists 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.

Fig. B-1 Microscope Schematic for Measuring Lateral Centering Error



B-2.2 Radial Centering

As shown in Fig. B-2, 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 μm (e.g., an LVDT gage) 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

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

To see why this is the case, note that, 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 $d/2$ 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

Fig. B-2 Setup for Measuring Radial Centering Error

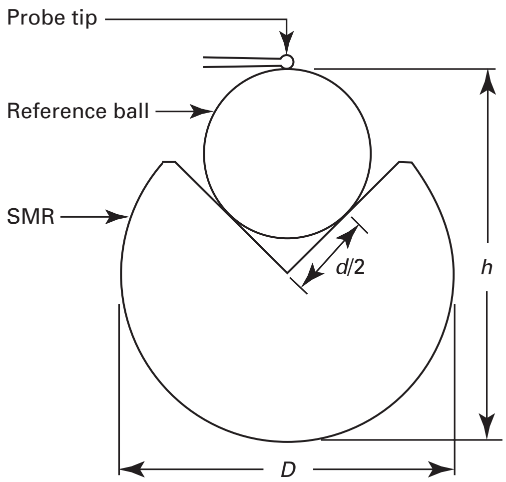


Fig. B-3 Beam Orientations That Minimize Effects of Dihedral Angle Errors

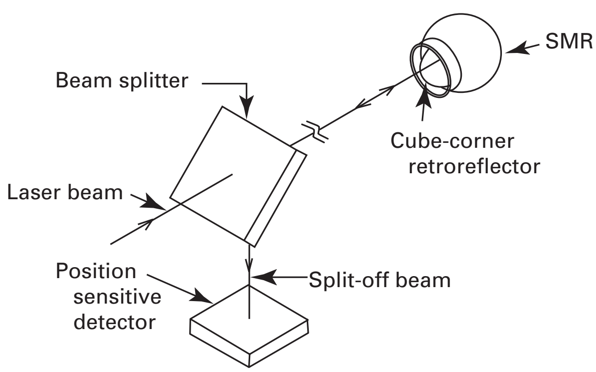


Fig. B-4 Laser Path With Unintended Offset Between Incoming and Outgoing Beams

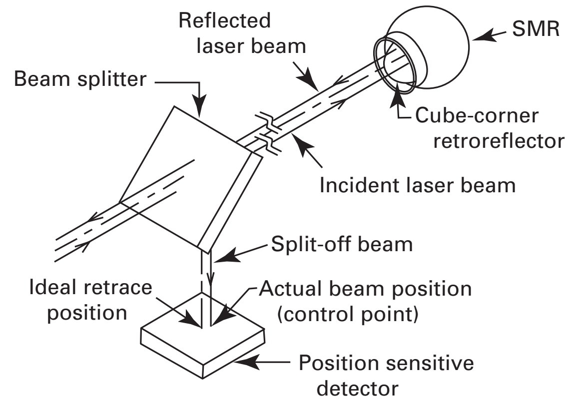
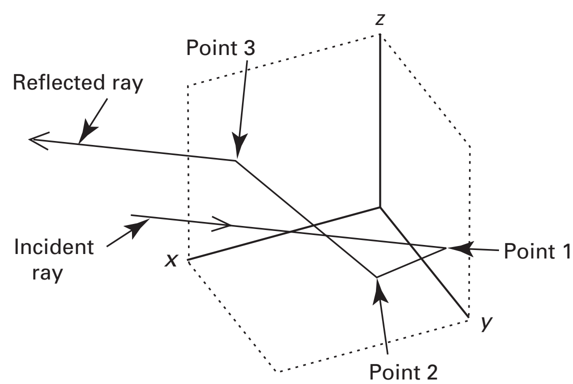


Fig. B-5 Path of Laser Beam in Cube Corner Retroreflector



Three Mutually Perpendicular Mirrors

height of a reference ball within an ideal SMR is then the sum of these three quantities or $D/2 + d\,(1 + \sqrt{3})/2$.

B-3 DIHEDRAL ANGLE ERRORS

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 arc seconds. This difference, called the *dihedral-angle error*, can degrade laser tracker performance if the SMR is used with an instrument that does not maintain perfect laser-beam retrace.

First consider the perfect retrace condition shown in Fig. B-3. 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 particular point on the surface of the PSD is designated as the control point. The laser tracker's servo system drives the beam steering mirror system 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 Fig. B-4, 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 Fig. B-5. The three mirrors lie in the *x*-*y* plane, the *y*-*z* plane, and the *z*-*x* plane respectively. The ray first strikes the *y*-*z* plane at point 1, then the *x*-*y* plane at point 2, and finally the *z*-*x* plane at point 3. The ray of light emerges from point 3 parallel to the ray incident on point 1.

Figure B-6 shows these same three points as viewed in a plane perpendicular to the axis of symmetry of the

Fig. B-6 Top View of Laser Beam Path in Cube Corner Retroreflector

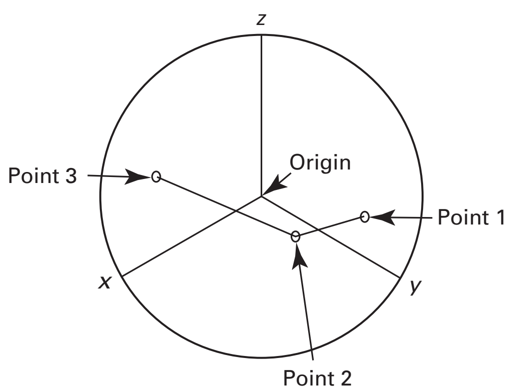
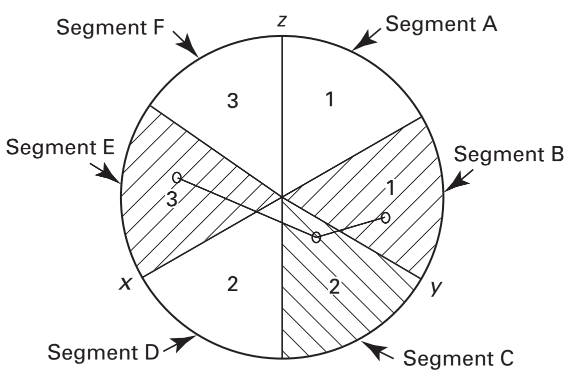


Fig. B-7 Top View of Cube Corner With Extended Lines of Intersection

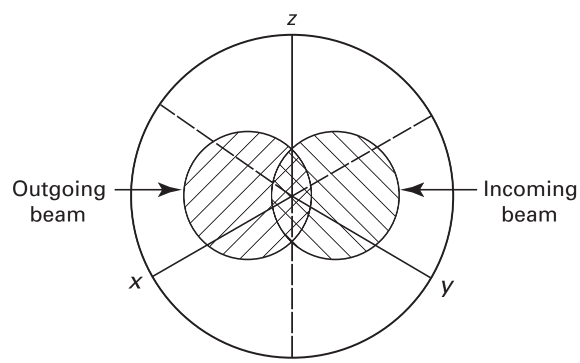


cube corner. Note that if the ray reverses its direction and begins at point 3, it will travel to point 2 and then point 1. Also note that the origin (vertex) of the cube corner bisects the line segment connecting points 1 and 3.

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 Fig. B-7. 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 Fig. B-7. Then, as a specific example, such rays incident on segment B may bend outward (leftward) by one arc second when they emerge from segment E. In this case, rays incident on segment E bend outward (rightward) by the same angle (one arc second) when they emerge from segment B.

Fig. B-8 Laser Beams Superimposed on Top View of Dihedral Prism

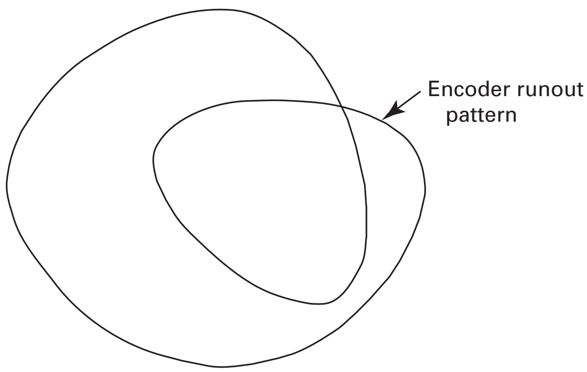


In general, collimated laser light incident on all six segments separates into six distinct segments after reflection. Each segment travels in a slightly different direction. Opposing segments (i.e., segments A-D, B-E, and C-F) bend in equal and opposite directions. Because of this symmetry, if the incoming 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 Fig. B-3 prevails.

Now suppose that the wrong control point has been chosen for the PSD. As shown in Fig. B-4, the incoming and outgoing laser beams do not coincide. For the case shown in Fig. B-8, 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 one arc second and the rays from B bend right by one arc second, then the left bending rays will dominate. The reflected beam then strikes the PSD off the control point, causing the servo system of the laser tracker to redirect the beam. The result is a change in the angles measured by the device's angular encoders.

This potential error in the measured angle is ordinarily removed by the laser tracker's compensation procedures. However, in two particular situations the compensation is not sufficient to remove these errors. In the first situation, the laser tracker operator uses more than one SMR in a particular measurement. In the second situation, the operator fails to hold the roll angle of the SMR fixed. Roll angle is defined as the angle of the SMR about the cube corner's axis of symmetry. Usually, SMRs are shipped with a particular mark along the rim of the SMR, which the operator holds at a fixed roll angle. For example, the mark may be consistently held in the uppermost position. Failure to hold the roll angle of the

Fig. B-9 Encoder Runout Pattern



SMR at a consistent position may introduce a measurement error.

This error can be seen by rotating the SMR about its axis of symmetry. This produces a runout pattern in the measured azimuth and zenith angles or, equivalently, in the transverse coordinates (side-to-side distance coordinates). When the SMR has a dihedral-angle error and the laser tracker has a control-point error, the runout pattern takes the form of a loop that repeats itself twice in each 360-deg rotation of the SMR. In contrast, the runout pattern caused by a lateral SMR centering error repeats itself once in each 360-deg rotation. For the general case in which both types of errors are present, the runout pattern forms a double-loop in each 360-deg rotation. An example of such a pattern is shown in Fig. B-9.

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 interferometer 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 multi-layer stack of thin dielectric films, or a reflective metal topped with a protective dielectric stack. Regardless of the type of coating, however, 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.

NONMANDATORY APPENDIX C
REFRACTIVE INDEX OF AIR

C-1 INTRODUCTION

This Appendix describes environmental phenomena that may affect the results of measurements performed using a laser tracker. The manufacturer should have accounted for the effects described in this section in establishing the rated conditions of section 3.

C-2 PHASE REFRACTIVE INDEX

The phase refractive index[1] is defined by eq. (C-1).

$$n = \frac{c_0}{c} \tag{C-1}$$

where
c_0 = velocity of light in vacuum
c = velocity of light in a medium (phase velocity)

The phase refractive index is used for displacement measurements that are based on interferometric fringe counting of a fixed wavelength of laser light.

The length scale of a displacement interferometer operating in air is

$$\lambda_{\text{air}} = \frac{\lambda_0}{n} \tag{C-2}$$

where
λ_0 = vacuum wavelength
n = phase refractive index of the air

NOTE: In this Appendix, the term *refractive index*, used without a modifier, is taken to mean the *phase refractive index*.

C-3 GROUP REFRACTIVE INDEX

The group refractive index is defined by

$$n_g = n - \lambda \frac{dn}{d\lambda} \tag{C-3}$$

where λ is the wavelength of the light source.

The group refractive index is used for absolute distance measurements where the amplitude or polarization of a light source is modulated. At optical and near-infrared wavelengths, the group refractive index is larger than the phase refractive index by a few parts in 10^6.

[1] Rüeger, J. M., *Electronic Distance Measurement: An Introduction*, 4th Ed., Springer, Berlin, 1996.

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 due to Ciddor[2] and Ciddor & Hill[3] are recommended for use with this Standard. These equations are valid over a wide range of wavelengths (300 nm to 1690 nm), temperatures (−20°C to 100°C), pressures (800 hPa to 1 200 hPa), and humidity (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 10^8, a level required in only the highest level of length metrology.

The Ciddor equation[4] 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 system. Corresponding results for ADM measurements can be derived using group refractive index values appropriate for the wavelength of the ADM light source.

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 systems. For such interferometers, and for levels of uncertainty required in laser tracker performance evaluation, a simplified equation[4] can be used to calculate the refractive index of air.

[2] Ciddor, P. E., "Refractive Index of Air: New Equations for the Visible and Near Infrared," *Applied Optics*, Vol. 35, 1566–1573, 1996.

[3] Ciddor, P. E. and Hill, R.J., "Refractive Index of Air: 2. Group Index," *Applied Optics*, Vol. 38, 1663–1667, 1999.

[4] See http://emtoolbox.nist.gov/Wavelength/Abstract.asp.

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

where

P = air pressure, kPa (101.325 kPa = 760 mmHg)
RH = relative humidity, % ($0\% \le RH \le 100\%$)
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 interferometer beam path.

C-5 REFRACTIVE INDEX UNCERTAINTY AND DISPLACEMENT MEASUREMENTS

At the levels of uncertainty required for the performance 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 errors.

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

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

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

Consider an interferometer 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

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

where L_{vac} is the displacement that would be measured in 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 $n \approx 1$,

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

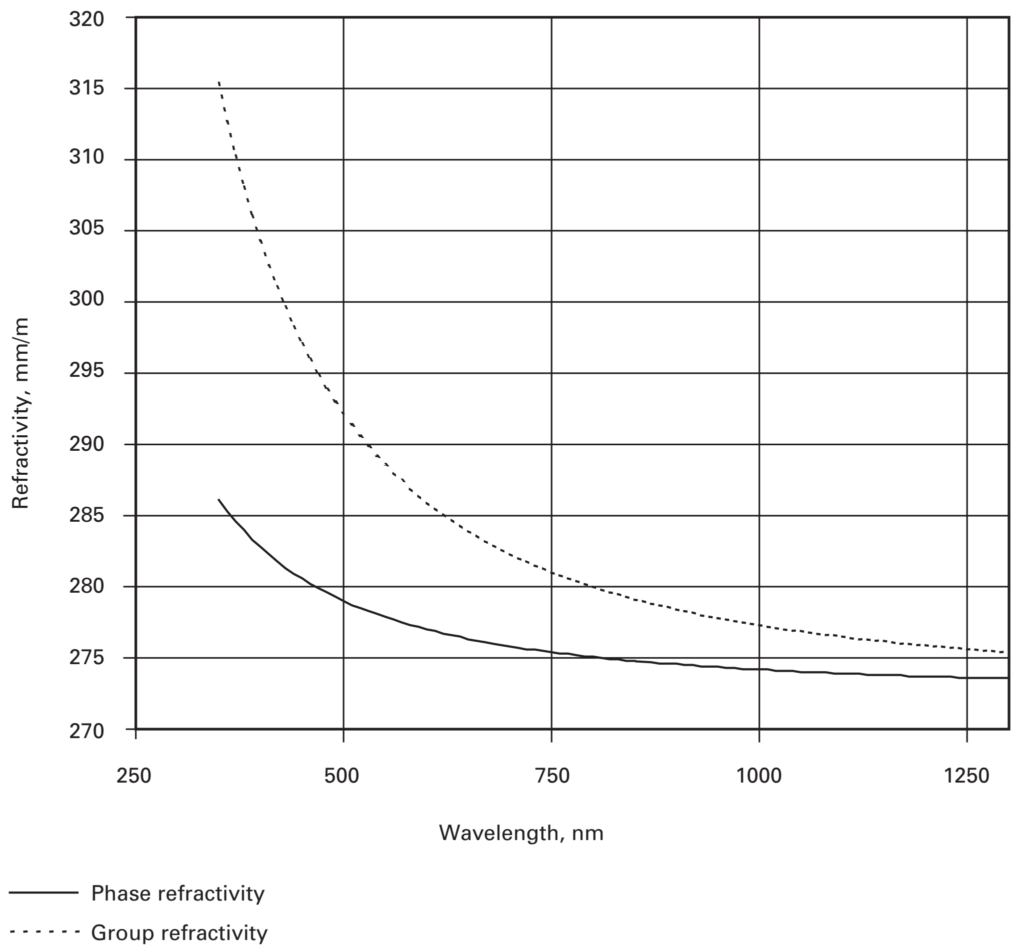
using the uncertainty given by eq. (C-5).

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-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 Ciddor[2] to be air at 15°C, 1013.25 hPa, 0.045% CO_2 content with 0% humidity.

Fig. C-1 Refractivity for Standard Dry Air



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

NONMANDATORY APPENDIX D
REFERENCE LENGTHS FOR LASER TRACKER SYSTEM TESTS

D-1 INTRODUCTION

The laser tracker system performance tests in this Standard consist of measuring a number of reference lengths at a prescribed set of positions and orientations within the instrument working volume. For each point-to-point length measurement, the difference between the measured length and the reference length is compared with a stated maximum permissible error (*MPE*) in order to decide conformance with specification.

This Appendix describes three forms of realization for a reference length as follows:

(a) Section D-2: a calibrated scale bar

(b) Section D-3: two retroreflector target nests on free-standing structures

(c) Section D-4: a laser rail system

Particular emphasis is placed on evaluating the uncertainty of the reference length. If the uncertainty is too large, conformance or nonconformance cannot be decided using the default decision rules of this Standard. Additional useful information on thermal effects can be found in ASME B89.6.2-1973.

D-2 REFERENCE LENGTH REALIZED USING CALIBRATED SCALE BAR

Consider a scale bar that has been calibrated at a temperature T_0. The reference length realized at temperature T_0 is L^0_{ref}, with a standard uncertainty $u(L^0_{\mathrm{ref}})$. The standard uncertainty $u(L^0_{\mathrm{ref}})$ is evaluated based upon the details of the calibration process, and includes a component due uncertainty in the nominal temperature T_0.

D-2.1 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

$$L_{\mathrm{ref}} = L^0_{\mathrm{ref}}\left[1 + (CTE)(T - T_0)\right] \qquad \text{(D-1)}$$

where *CTE* is the coefficient of thermal expansion of the scale bar.[1]

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

Because the correction cannot be performed exactly, the uncertainty $u(L^0_{\mathrm{ref}})$ in the reference length will be greater than $u(L_{\mathrm{ref}})$ whenever $T \neq T_0$ during laser tracker performance evaluation.

D-2.2 Evaluation of Uncertainty in Reference Length

The standard uncertainty of the reference length is calculated from expression (eq. D-1) using the law of propagation of uncertainty.

$$u^2(L_{\mathrm{ref}}) = \left(\frac{\partial L_{\mathrm{ref}}}{\partial L^0_{\mathrm{ref}}}\right)^2 u^2(L^0_{\mathrm{ref}}) + \left(\frac{\partial L_{\mathrm{ref}}}{\partial CTE}\right)^2 u^2\,(CTE) + \left(\frac{\partial L_{\mathrm{ref}}}{\partial T}\right)^2 u^2\,(T) \qquad \text{(D-2)}$$

Note that there is no uncertainty component associated with the nominal calibration temperature T_0, which is taken to be a constant in eq. (D-1) since it is already included in the uncertainty of the calibration of the scale bar, i.e., L^0_{ref}.

The sensitivity coefficients in eq. (D-2) follow from the form of eq. (D-1),

$$\frac{\partial L_{\mathrm{ref}}}{\partial L^0_{\mathrm{ref}}} + \left[1 + (CTE)(T - T_0)\right] \approx 1 \qquad \text{(D-3)}$$

assuming that $(CTE)(T - T_0) \ll 1$,

$$\frac{\partial\, L_{\mathrm{ref}}}{\partial\,(CTE)} = L^0_{\mathrm{ref}}(T - T_0) \qquad \text{(D-4)}$$

$$\frac{\partial L_{\mathrm{ref}}}{\partial T} = L^0_{\mathrm{ref}} \cdot CTE \qquad \text{(D-5)}$$

With these results, eq. (D-2) becomes

$$u^2(L_{\mathrm{ref}}) = u^2(L^0_{\mathrm{ref}}) + \left[L^0_{\mathrm{ref}}(T - T_0)\right]^2 u^2(CTE) + (L^0_{\mathrm{ref}} \cdot CTE)^2\, u^2(T) \qquad \text{(D-6)}$$

Equations (D-1) and (D-6) give the desired formulas for calculating the corrected reference length and the associated standard uncertainty when using the scale bar at a temperature other than T_0.

D-2.3 Decision Rule for Deciding Conformance With MPE Specification

For any particular point-to-point length measurement, the measurand δ is the magnitude of the difference between the measured length L_m, as indicated by the laser tracker display, and the reference length L_{ref}:

$$\delta = |L_m - L_{\text{ref}}| \quad \text{(D-7)}$$

The value of δ is compared with the manufacturer's maximum permissible error (*MPE*) specification in order to make a pass/fail decision.

In this Standard, a 4:1 simple acceptance and rejection decision rule is used. With simple 4:1 acceptance/rejection, a test result is accepted if $\delta \leq MPE$, and rejected otherwise, provided that $C_m \geq 4$, where C_m is the *measurement capability index*, defined by

$$C_m = \frac{MPE}{2u(\delta)} = \frac{MPE}{U} \quad \text{(D-8)}$$

Here $u(\delta)$ is the standard uncertainty associated with the result of the measurement, and $U = 2u(\delta)$ is the $k = 2$ expanded uncertainty.

The standard uncertainty $u(\delta)$ is calculated from eq. (D-7), using the law of propagation of uncertainty

$$\begin{aligned} u^2(\delta) &= \left(\frac{\partial \delta}{\partial L_m}\right)^2 u^2(L_m) + \left(\frac{\partial \delta}{\partial L_{\text{ref}}}\right)^2 u^2(L_{\text{ref}}) \quad \text{(D-9)} \\ &= u^2(L_m) + u^2(L_{\text{ref}}) \end{aligned}$$

For the purposes of this Standard, the measured length L_m is taken to be an exact number, so that $u^2(L_m) = 0$. The standard uncertainty $u(\delta)$ is then equal to the standard uncertainty associated with the reference length L_{ref}:

$$u(\delta) = u(L_{\text{ref}}) \quad \text{(D-10)}$$

From eq. (D-8) it then follows that the uncertainty in the value of the reference length must be small enough so that

$$C_m = \frac{MPE}{2u(L_{\text{ref}})} \geq 4 \quad \text{(D-11)}$$

As shown in eq. (D-6), using a calibrated scale bar at a temperature other than its calibration temperature will always increase the uncertainty of the realized reference length and decrease the measurement capability index C_m.

D-2.4 Example

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

The reference length for the performance tests is realized by use of an Invar scale bar of nominal length 3.0 m and nominal *CTE* of $2 \times 10^{-6}\,°\text{C}^{-1}$. The scale bar has been calibrated at 20°C ± 0.1°C in a temperature-controlled metrology laboratory.

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

A performance test is performed on the shop floor when the average temperature of the scale bar is estimated to be 25°C ± 0.5°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 manufacturer's performance specification states a maximum permissible error (*MPE*) of 60 µm when measuring a point-to-point nominal length of 3.0 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 a decision can be made as to conformance of the measured error, the measurement capability index C_m must be evaluated in order to ensure that it satisfies the 4:1 simple acceptance requirement: $C_m = MPE/2u(L_{\text{ref}}) \geq 4$, with $MPE = 60$ µm.

The uncertainty $u(L_{\text{ref}})$ in the reference length in the conditions on the shop floor is calculated using eq. (D-6). The required uncertainty components are evaluated as follows:

(a) The standard uncertainty $u(L^0_{\text{ref}})$ in the calibrated reference length found from the calibration certificate

$$U_{k=2} = 2u(L^0_{\text{ref}}) = 10\ \mu\text{m}$$

so that

$$u(L^0_{\text{ref}}) = 5\ \mu\text{m} \quad \text{(D-12)}$$

(b) The uncertainty $u(T)$ of the scale bar temperature during the test, assuming a uniform distribution of full width 1.0°C about the best estimate of 25°C is

$$u(T) = 0.5°\text{C}/\sqrt{3} \quad \text{(D-13)}$$

The uncertainty component due to temperature uncertainty is then

$$\begin{aligned} (L^0_{\text{ref}} \bullet \text{CTE})^2\, u^2(T) &= (3.0 \times 2)^2 \times \left(\frac{0.5}{\sqrt{3}}\right)^2 \mu\text{m}^2 \quad \text{(D-14)} \\ &= 3.0\ \mu\text{m}^2 \end{aligned}$$

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

$$u(CTE) = 0.5 \times 10^{-6}\,°\text{C}^{-1}/\sqrt{3} \quad \text{(D-15)}$$

The uncertainty component due to CTE uncertainty is then

$$[L^0_{\mathrm{ref}}(T-T_0)]^2\, u^2(CTE) = (3.0 \times 5)^2 \times \left(\frac{0.5}{\sqrt{3}}\right)^2 \mu\mathrm{m}^2 \approx 18.6\ \mu\mathrm{m}^2 \quad \text{(D-16)}$$

Then from eq. (D-6):

$$u^2(L_{\mathrm{ref}}) = (25.0 + 18.6 + 3.0)\ \mu\mathrm{m}^2 = 46.6\ \mu\mathrm{m}^2 \quad \text{(D-17)}$$

or

$$u(L_{\mathrm{ref}}) \approx 6.8\ \mu\mathrm{m} \quad \text{(D-18)}$$

Thus the measurement capability index is

$$C_m = 60/(2 \times 6.8) \approx 4.4 \quad \text{(D-19)}$$

which satisfies requirement of eq. (D-11) for a simple 4:1 acceptance decision rule.

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

$$L_{\mathrm{ref}} = 3.010125(1 + 2 \times 10^{-6} \times 5)\ \mathrm{m} = 3.010155\ \mathrm{m} \quad \text{(D-20)}$$

From eq. (D-7), the magnitude of the measured length difference is

$$\delta = |L_m - L_{\mathrm{ref}}| = (3.010190 - 3.010155)\ \mathrm{m} = 35\ \mu\mathrm{m} \quad \text{(D-21)}$$

Since δ is less than the stated MPE of 60 μm and $C_m > 4$, the laser tracker meets the manufacturer's MPE specification for this test.

Note that in this example the thermally related uncertainty sources were significant. For laser trackers with smaller *MPE*s an in situ calibration of the scale bar at the temperature of the test environment could significantly reduce these uncertainty sources.

D-3 REFERENCE LENGTH REALIZED USING TARGET NESTS ON FREESTANDING STRUCTURES

In this method of realizing a reference length, retroreflector target kinematic nests are mounted on each of two stable structures, such as the commercially available tripod stands used for mounting optical tooling. 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 a target retroreflector as it is moved from one nest to the other. This measured displacement is the reference length realized by the two retroreflector 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 instrument should be aligned relative to the two nests so that the distance between them can be measured using the interferometer only (i.e., a purely radial measurement).

D-3.1 Reference Length Uncertainty

There are several ways to evaluate the uncertainty of point-to-point reference lengths using an integral IFM system that has passed one of the tests of para. 6.4.2.

(a) 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 $e_{\max} = D + LDE(L_{\mathrm{ref}})$, where D is a drift component and $LDE(L_{\mathrm{ref}})$ is a length-dependent term. The standard uncertainty $u(L_{\mathrm{ref}})$ is then evaluated by assigning a uniform distribution of width to the possible measurement error, so that $u(L_{\mathrm{ref}}) = e_{\max}/\sqrt{3}$.

(b) 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 $L_1, \ldots, L_N$ yields a corresponding set of observed errors $E_1, \ldots, E_N$. The relative, or fractional errors, regardless of sign, for these results are $r_1, \ldots, r_N$, where $r_k = |E_k|/L_k$, $k = 1, \ldots, N$. The largest relative error $r_{\max} = \max(r_k)$ 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 $e_{\mathrm{ref}} = r_{\max} L_{\mathrm{ref}}$, and assigning a uniform distribution of width $2r_{\mathrm{ref}}L_{\mathrm{ref}}$ yields a standard uncertainty $u(L_{\mathrm{ref}}) = r_{\max}L_{\mathrm{ref}}/\sqrt{3}$.

NOTE: If the IFM is tested using a set of short calibrated lengths and the nonlength-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 system using calibrated lengths within 400 mm of the nominal length of 2.3 m.

(c) The uncertainty of a radial displacement measurement of a reference length L_{ref} can be evaluated from first principles, using known properties of laser beams propagating in air. This approach is detailed in para. D-3.2.

In each of these cases, passing one of the test procedures of para 6.4.2 provides evidence that the stated uncertainty is achievable.

D-3.2 Uncertainty in Reference Length Due to Wavelength Compensation Errors

From the basic physics of interferometric displacement interferometry, the connection to the SI definition of the meter using an IFM system is via the vacuum wavelength λ_{vac} of the laser source. Most commercial laser trackers use a frequency stabilized helium-neon laser whose vacuum wavelength 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 is 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 instrument's weather station. The reference length L_{ref} is then given by

$$L_{ref} = L_m(1 - c_P\Delta P - c_T\Delta T) \tag{D-22}$$

In eq. (D-22), $c_P\Delta P$ and $c_P\Delta T$ are corrections for possible differences $\Delta P = P - P_0$ and $\Delta T = T - T_0$ between the average air pressure P and temperature T along the IFM beam path and the sensor values P_0 and T_0 used in the calculation of the wavelength compensation.[2] 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 $\lambda \approx 633$ nm, the coefficients c_P and c_T are given by

$$c_P = 2.7 \times 10^{-9}\ \text{Pa}^{-1} \tag{D-23}$$

$$c_T = -1.0 \times 10^{-6}\ {}^\circ\text{C}^{-1} \tag{D-24}$$

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-22), the best estimate of the reference value is

$$(L_{ref})_{est} = L_m \tag{D-25}$$

The standard uncertainty $u(L_{ref})$ associated with the best estimate is computed from eq. (D-22) using the law of propagation of uncertainty:

$$u^2(L_{ref}) = u^2(L_m) + L_m^2\left[c_p^2u^2(\Delta P) + c_T^2u^2(\Delta T)\right] \tag{D-26}$$

The length L_m indicated by the laser tracker display is taken to be an exact number, so that $u^2(L_m) = 0$, and

$$u^2(L_{ref}) = L_m^2\left[c_P^2u^2(\Delta P) + c_T^2u^2(\Delta T)\right] \tag{D-27}$$

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

$$u(\Delta P) = |\Delta P|_{max}/\sqrt{3}$$

and

$$u(\Delta T) = |\Delta T|_{max}/\sqrt{3}$$

The standard uncertainty of the reference length is then

$$u(L_{ref}) = L_m\sqrt{\frac{c_P^2|\Delta P|_{max}^2}{3} + \frac{c_T^2|\Delta T|_{max}^2}{3}} \tag{D-28}$$

D-3.3 Example

The IFM ranging system of a laser tracker is aligned so as to perform a radial measurement (constant IFM beam direction) of the distance between of a pair of kinematic target nests. The result of the measurement is $L_m = 3.215000$ 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.

Based upon experience, the locations of the laser tracker environmental sensors, and the particular test environment, maximum air pressure and temperature deviations are estimated to be $|\Delta P|_{max} = 3$ mm Hg ≈ 400 Pa and $|\Delta T|_{max} = 2$°C. The standard uncertainty is then calculated using eq. (D-28):

$$u(L_{ref}) = 3.215\ \text{m} \times \sqrt{\frac{(2.5 \times 10^{-9})^2(400)^2 + (1 \times 10^{-6})^2(2)^2}{3}} \approx 4.2\ \mu\text{m} \tag{D-29}$$

Then, from para. D-2.3, the measurement capability index is

$$C_m = \frac{MPE}{2u(L_{ref})} = \frac{50\ \mu\text{m}}{8.4\ \mu\text{m}} \approx 6 \tag{D-30}$$

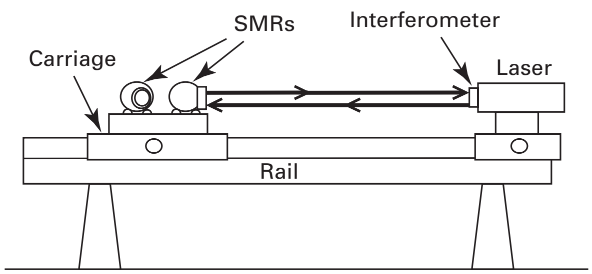
Thus, $C_m > 4$, and the realized reference length can be used for point-to-point length measurement systems tests.

D-3.4 Stability of Reference Length Realized Using Target Support Structures

If the thermal environment departs significantly from the conditions that existed during the establishment of the reference length, there is a possibility that this length will change due to relative motion of the structures that carry the kinematic target nests. It is recommended, in case of doubt about a possible drift in the value of the reference length, that this length be remeasured as necessary in order to assure that the measurement capability satisfies the requirement $C_m \geq 4$.

[2] The effect of a possible humidity error is assumed to be negligible.

Fig. D-1 Schematic of Laser Rail System



D-4 REALIZATION OF REFERENCE LENGTHS USING LASER RAIL SYSTEM

A laser rail system containing a separate displacement interferometer, external to the laser tracker, can be used to establish reference lengths. A schematic of such a laser rail system is shown in Fig. D-1. Typically, two SMR targets are mounted on the laser rail carriage. One is used by the external laser interferometer to measure the displacement of the carriage, and the second is the target for the laser tracker under test.

Care must 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 retroreflector 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-4.2 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 a laser rail system can be found in "A Laser Tracker Calibration System."[3]

D-4.1 Cosine Error

By careful alignment of the external laser interferometer beam along the rail direction, the cosine error can be made negligible. This requires that the direction defined by the external interferometer laser beam be the same direction as that of the carriage travel. This can be checked by observing the location of the external laser interferometer's beam spot on a target covering its SMR and ensuring that this beam spot location does not significantly shift as the carriage moves along the rail. For example, a 1 mm shift in the laser beam spot location for a carriage motion of 1 m produces a relative error of less than 1×10^{-6}, and this error decreases rapidly (for a given beam spot shift) as the carriage travel length increases.

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

D-4.2 Abbé Error

Due to space limitations, the centers of the SMR for the external interferometer and the SMR for the laser tracker do not coincide.[4] Abbé errors occur when the laser tracker's SMR is offset orthogonal to the reference line defined by the external interferometer laser beam, and the carriage changes its angular orientation between the initial and final positions of the carriage that define the reference length. A change in angular orientation may be due to either a pitch or yaw of the carriage, and when multiplied by the orthogonal offset distance (known as the Abbé offset) results in an Abbé error.

The Abbé error can be estimated by resolving the Abbé offset into its vertical and horizontal components. The two components of the Abbé error can then be calculated as follows. The first is obtained by multiplying the vertical component of the Abbé offset by the difference in pitch of the carriage in the two positions that define the reference length. This error is depicted in Fig. D-2, illustration (a). The second error is obtained by multiplying the horizontal component of the Abbé offset by the difference in yaw of the carriage in the two positions that comprise the reference measured length. This length error is depicted in Fig. D-2, illustration (b). To estimate the magnitude of the Abbé error, these two errors are added in quadrature, so that

$$\varepsilon_{\text{Abbé}} = \sqrt{\varepsilon_1^2 + \varepsilon_2^2} \tag{D-31}$$

where

ε_1 = vertical component of the Abbé error
ε_2 = horizontal component of the Abbé error

The magnitude of these errors can be estimated using the chart in Fig. D-3.

The standard uncertainty associated with the Abbé error can be evaluated by

$$u(\text{Abbé}) = \frac{\varepsilon_{\text{Abbé}}}{\sqrt{3}} \tag{D-32}$$

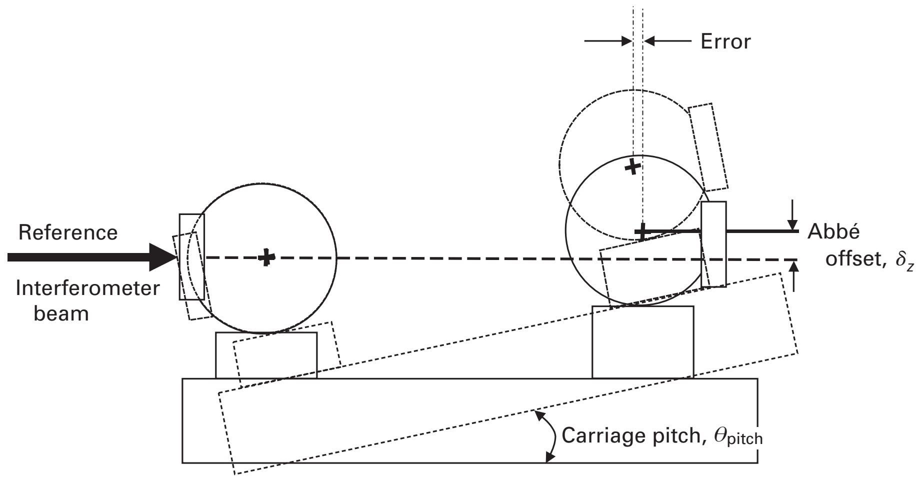
EXAMPLE: The change in pitch and yaw, without regard to sign, of the target carriage at the two points that define the reference length are 60 and 70 arc-seconds respectively. The Abbé offset in the vertical and horizontal directions are 5 mm and 4 mm, respectively. From this information the components of the Abbé error can be estimated from Fig. D-3. The chart gives $\varepsilon_1 \approx \varepsilon_2 \approx$ 1.4 μm. Then, using eqs. (D-31) and (D-32), the magnitude of the expected error is approximately 2.0 μm and the associated standard uncertainty is approximately 1.2 μm.

D-4.3 Uncertainty Due to Wavelength Compensation Errors

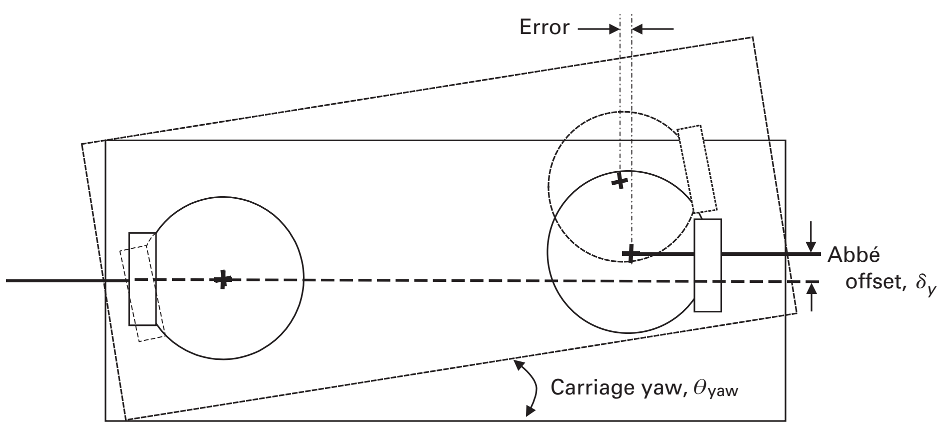
In addition to possible Abbé errors, a reference length realized using a laser rail system is subject to errors

[4] The use of a glass sphere with a refractive index of two, a so-called $n = 2$ sphere, would be an exception. However, at the time of this writing such spheres are not readily available.

Fig. D-2 Illustrating the Origin of Abbé Errors



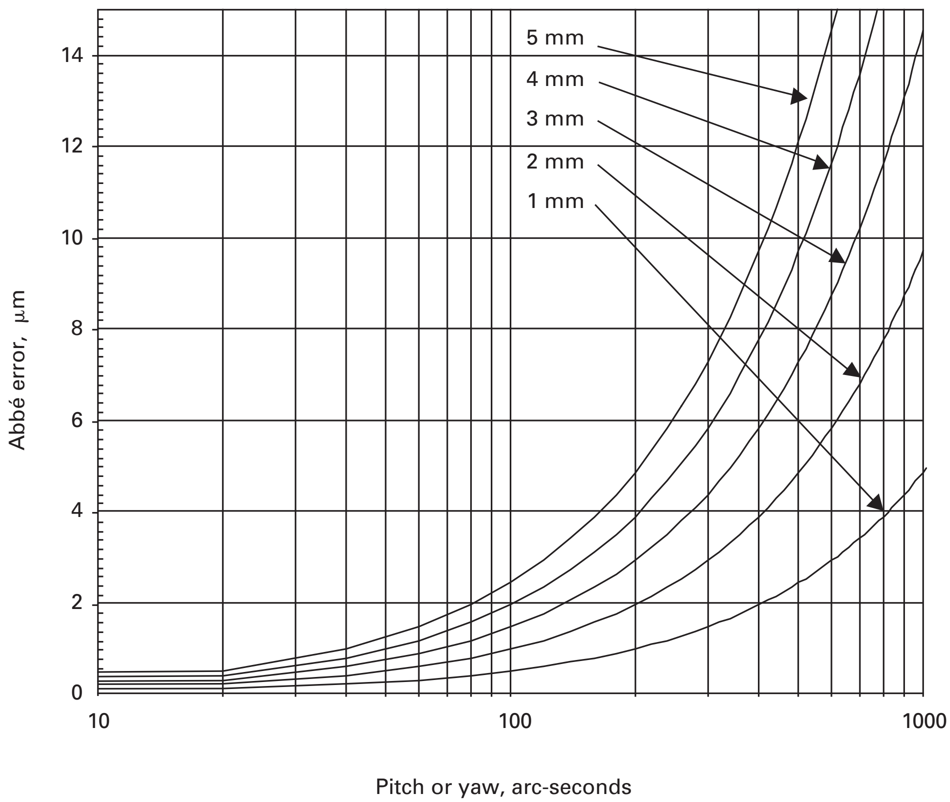
(a) Side View



(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.

Fig. D-3 Abbé Error Versus Carriage Angular Motion for Various Values of Abbé Offset



associated with the correction for atmospheric conditions. Follow the procedure described in para. D-3.1 to evaluate the standard uncertainty associated with errors in air temperature and pressure values used in compensating the measured displacement for the refractive index of air.

D-4.4 Rail Stability

Care must be taken to ensure that the rail is physically stable when the carriage is displaced along the rail axis. Otherwise the external interferometer, which is attached to the rail, will not detect the physical motion of the entire rail system during this carriage travel, whereas the laser tracker will detect the rail motion and hence the laser tracker and reference length measurements will not agree. An indicator referenced to the floor and indicating the location of the rail can detect motion of the entire rail system. Typically, this can be made a negligible source of uncertainty.

D-4.5 Combined Standard Uncertainty of Reference Length

The combined standard uncertainty for a reference length produced using a laser rail system is evaluated by combining the components due to imperfect wavelength compensation and Abbé error. Assuming negligible cosine and rail stability uncertainty components, the combined standard uncertainty $u(L_{\mathrm{ref}})$ is given by

$$u(L_{\mathrm{ref}}) = \left[L_m^2 \left(\frac{c_P^2 \left|\Delta P\right|_{\max}^2}{3} + \frac{c_T^2 \left|\Delta T\right|_{\max}^2}{3} \right) + \frac{\varepsilon_{\text{Abbé}}^2}{3} \right]^{1/2} \quad \text{(D-33)}$$

where c_P and c_T given by eqs. (D-23) and (D-24), and the component due to Abbé error by eq. (D-31).

NONMANDATORY APPENDIX E
EFFECT OF AIR TEMPERATURE ON LASER TRACKER MEASUREMENTS

E-1 INTRODUCTION

The test procedures of this Standard require that laser tracker specifications be accompanied by environmental conditions, including minimum temperature, maximum temperature, and temperature gradients (spatial gradients in °C/m and temporal gradients in °C/h.) 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 Equation for Radial Error

A laser tracker is set up to measure the displacement d from point P_1 to P_2. The true displacement is

$$d = \int_{P_1}^{P_2} ds \tag{E-1}$$

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 $T(s)$, and the laser beam has a speed $c/n[T(s)]$, 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 or 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 $n(T_m)$:

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

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:

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

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

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

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

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

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

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

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 $\partial n/\partial T = -1 \times 10^{-6}\ °\mathrm{C}^{-1}$. 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

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

If the distance to the target were 10 m, the radial error would be −15 μm. The minus sign means that the target is 15 μm 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

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

where

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

Detailed discussions of optical ray propagation may be found in *Principles of Optics*[1] 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:

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

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

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

$$\left.\frac{dx}{dz}\right|_{z'} = \frac{n(z_i)}{n(z')}\left.\frac{dx}{dz}\right|_{z_i} + \frac{1}{n(z')}\int_{z_i}^{z'}\frac{\partial n}{\partial T}\frac{\partial T}{\partial x}\,dz \tag{E-11}$$

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

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

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

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

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 $\partial T/\partial x = +1°\text{C·m}^{-1}$ 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

$$\frac{\partial T}{\partial x} = \begin{cases} +1°\text{C}\cdot\text{m}^{-1}, & 0 \le z < 4\text{ m} \\ +10°\text{C}\cdot\text{m}^{-1}, & 4\text{ m} \le z < 5\text{ m} \\ +1°\text{C}\cdot\text{m}^{-1}, & 5\text{ m} \le z < 10\text{ m} \end{cases} \tag{E-14}$$

$$\frac{\partial n}{\partial T} = -1 \times 10^{-6}\ °\text{C}^{-1} \tag{E-15}$$

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

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 $z = 10$ 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 below. See Figs. E-1, E-2, and E-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.

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

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

[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.

Fig. E-1 Change in Refractive Index Versus Transverse Distance, *x*

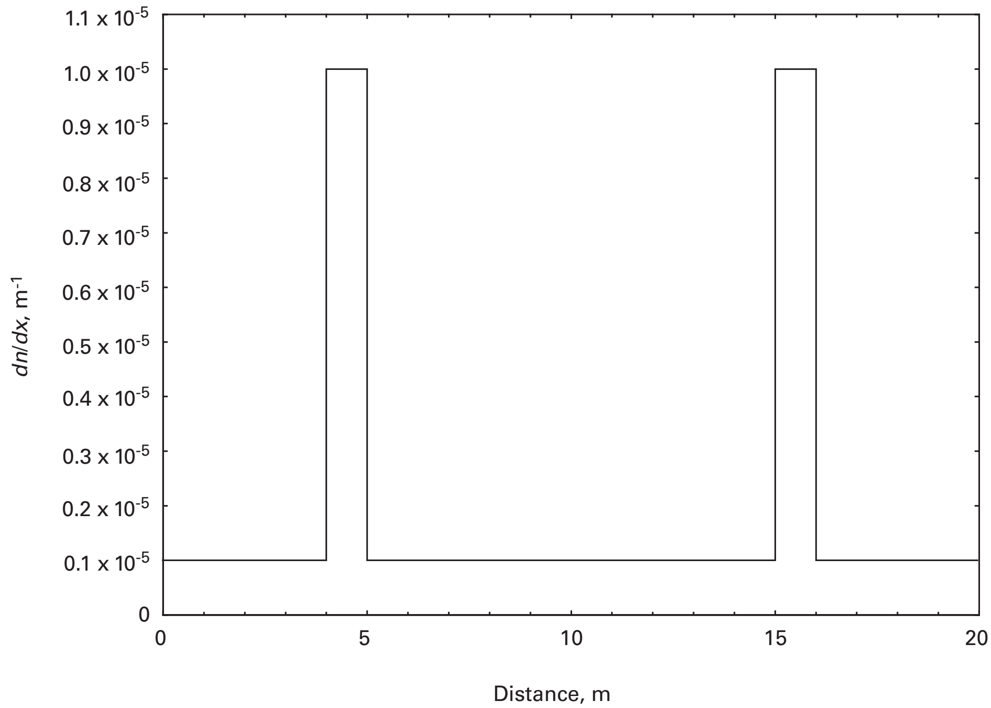


Fig. E-2 Angle of Laser Beam Versus Distance Traveled

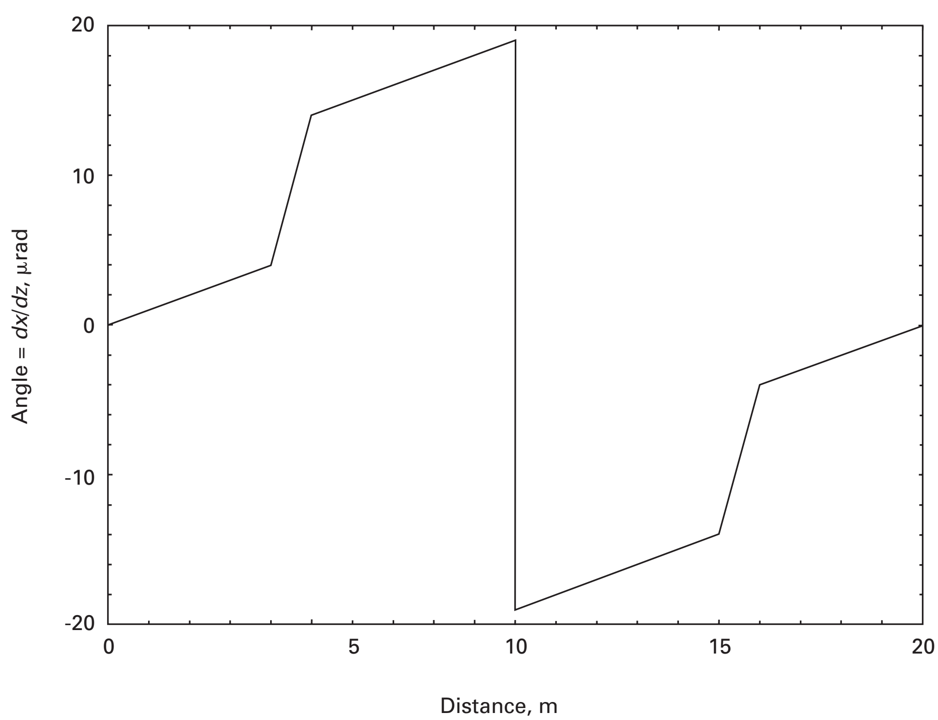
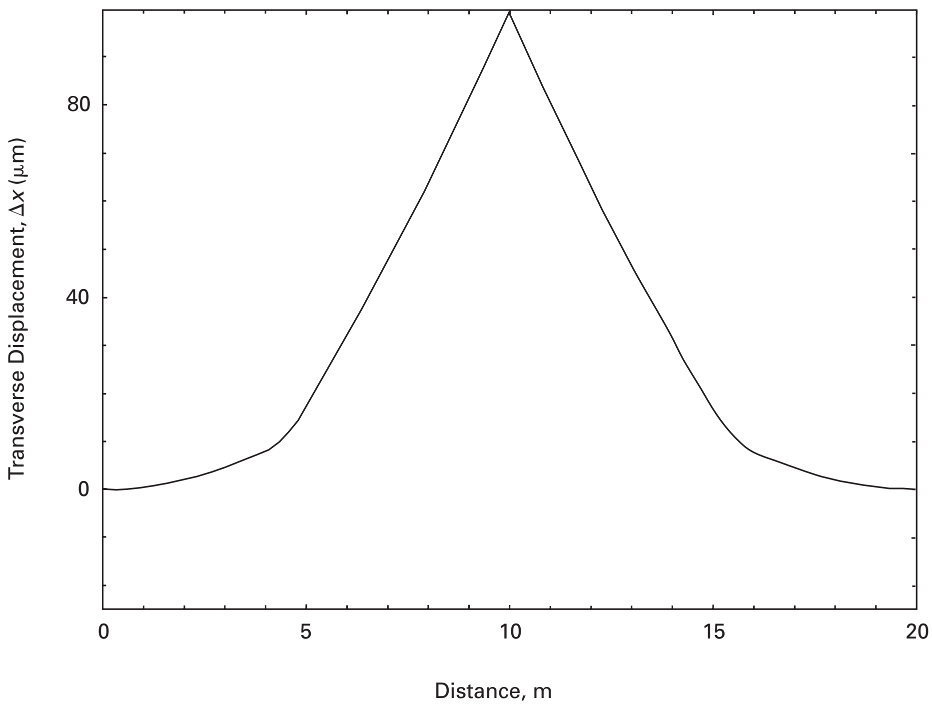


Fig. E-3 Transverse Displacement of Laser Beam Versus Distance Traveled



Eq. (E-9) The Ray Equation	Eq. (E-16) Newton's Second Law
Gradient, $\partial n/\partial x$	Acceleration, F_x/m
Distance, z	Time, t
Displacement, x	Displacement, x

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

$$e_x = \Delta x/z \tag{E-17}$$

The fractional error for the example above is shown in Fig. E-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 Fig. E-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

$$e_x = \frac{z}{2}\frac{\partial n}{\partial x} \tag{E-18}$$

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

$$\left|\frac{\partial n}{\partial x}\right|_{\text{max\_effect}} = \frac{z}{2} \cdot |e_x|_{\text{max slope}} \tag{E-19}$$

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 Fig. E-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 $9.95 \times 10^{-6}/5 \text{ m} = 1.99 \times 10^{-6} \text{ m}^{-1}$.

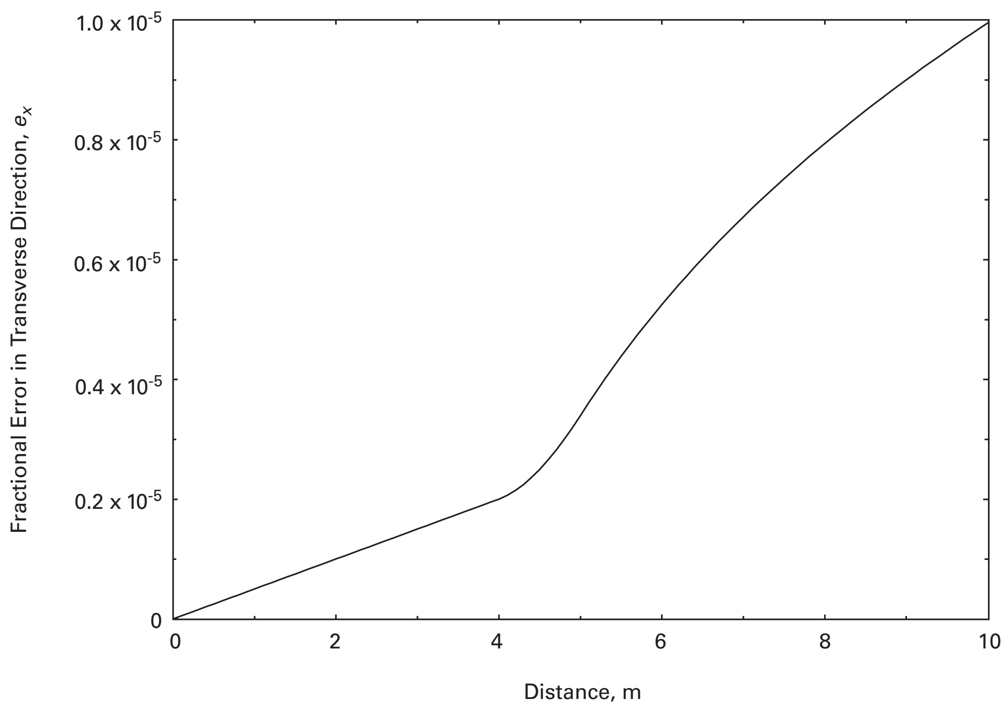
E-3 UNAMBIGUOUS ENVIRONMENTAL SPECIFICATIONS

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)

Fig. E-4 Fractional Error Versus Distance for Example



NONMANDATORY APPENDIX F
LASER TRACKER INTERIM TESTING

F-1 INTRODUCTION

Interim testing is designed to ensure that a measurement system is functioning properly between routine calibrations. Interim test procedures are expressly designed to be sensitive to changes in a measurement system 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. It is merely a quick system check and, consequently, should not be as extensive or as time consuming as a full performance evaluation. An interim test should be sensitive to as many error sources as possible so that the number of measurements required is kept relatively small and the time required to perform them is as short as practically possible.

Because of the wide array of laser tracker configurations, manufacturers often prescribe routine system checks that are sensitive to error sources that are common to the unique construction of their particular instruments. Hence, it is strongly suggested that the manufacturer's recommendations be carefully considered when developing procedures for interim testing. For example, one manufacturer prescribes a set of tests referred to as an *intermediate alignment*. These tests are designed to be sensitive to error sources that are caused by thermal changes in the operating environment. An instrument from another manufacturer might have a different set of error sources and thus require a different test procedure. Accordingly, the tests described in this Appendix are provided as a guideline in the event that such manufacturer-recommended procedures are either not available or insufficient for the measurement tasks being performed.

F-2 ENVIRONMENTAL CONSIDERATIONS

Interim testing should be performed in an environment that is similar to the one in which the instrument 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 in order to assure that the entire range of applicable operating environments is sufficiently sampled in the interim test procedures. 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 measurement system 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, and in a harsh environment. The frequency of testing is also strongly affected by balancing the cost of interim testing against the consequences 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 and/or safety critical workpieces may elect to perform daily tests, where other users might test weekly or monthly. Additionally, interim testing should be conducted after any sort of significant event such as subject to excessive vibrations or to potential damage.

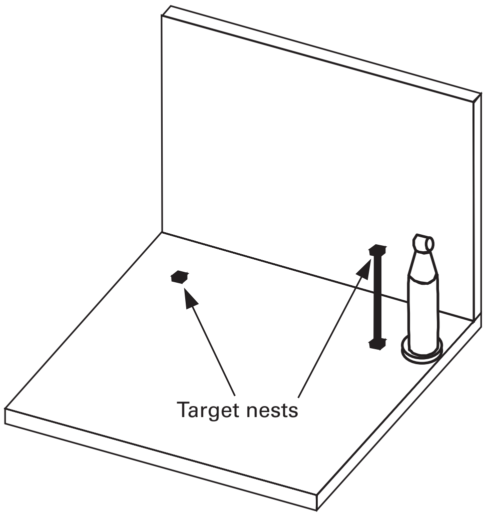
F-4 DEFAULT TEST PROCEDURES

The tests in this section describe a set of point-to-point length measurements and two-face tests similar to the ones discussed in section 6. In all cases, good measurement practices and proper metrological techniques should be employed to ensure the integrity of the measurement results.

F-4.1 Interim System Test 1

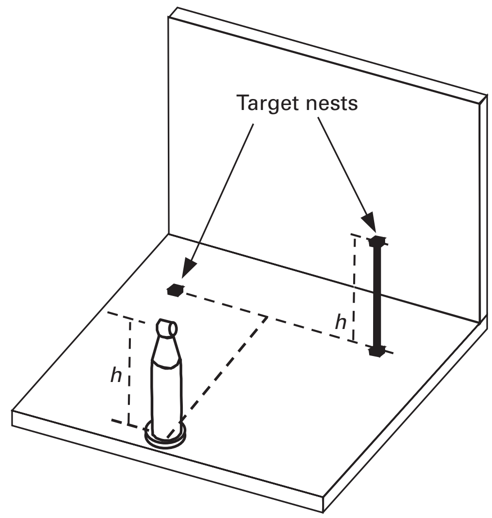
The first test employs a reference length at an inclined angle. Ideally, this would be an independently calibrated reference length, e.g. a calibrated scale bar. This is particularly important for a laser tracker that has only an ADM measurement capability. For laser trackers that include an IFM that has passed one of the test procedures of para. 6.4.2, the IFM may be used to realize a reference length by using a retro-reflector target and two target nests spaced approximately 2.3 m apart. One nest should be placed approximately at laser tracker height, and the other on the floor. The instrument should be aligned

Fig. F-1 Setup for Establishing Reference Length



GENERAL NOTE: The laser tracker should be aligned such that the reference length is measured with minimal angular motion. It may be necessary to use a turning mirror when aligning the laser tracker to perform this measurement.

Fig. F-2 Setup for Performing Length Measurement and Two-Face Tests



relative to the two nests so that the distance between them can be determined using the interferometer only (see Fig. F-1). This length should be measured and used as the reference length.

The interim test consists of placing the laser tracker so that it is approximately midway between the target nests (or scale bar) with the instrument placed as close as practically possible to the reference length (see Fig. F-2). The distance between the nests should be measured and the absolute value of the difference between the measured length and the reference length should not exceed the MPE for the measurement. This MPE should be calculated from the equation provided by the manufacturer (see section 3).

F-4.2 Interim System Test 2

With the laser tracker placed midway between the two target nests as illustrated in Fig. F-2, perform three two-face measurements with the retroreflector placed in each of the two target nests. Although this Standard does not require the manufacturer to provide an MPE for an arbitrary two-face measurement, the results of this test can be compared to the MPE for position number one of the two-face system tests described in para. 6.3.

ASME B89.4.19-2006

ISBN 0-7918-3004-7
9 780791 830048
L08306