ASME B89.4.19-2021

[Revision of ASME B89.4.19-2006 (R2015)]

# Performance Evaluation of Laser-Based Spherical Coordinate Measurement Systems

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AN AMERICAN NATIONAL STANDARD

The American Society of Mechanical Engineers

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[Revision of ASME B89.4.19-2006 (R2015)]

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AN AMERICAN NATIONAL STANDARD

The American Society of Mechanical Engineers
Two Park Avenue • New York, NY • 10016 USA

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# FOREWORD

ASME B89 Standards Committee 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 4 of the B89 Committee 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.

Performance evaluation of a laser tracker presents challenges different from those associated with conventional Cartesian CMMs. Because of a laser tracker's very large working volume, no full-scale, three-dimensional calibrated artifacts exist, and the design of the laser beam steering subsystem is such that individual parametric errors cannot, in general, be isolated and measured individually. For any coordinate measurement system, a test of the system's ability to realize the SI unit of length, the meter, is a fundamental requirement. In a laser tracker, the length scale is often a laser interferometer (IFM), and the person checking the system's ability to realize a meter usually 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 the manufacturer's maximum permissible error (MPE) specifications in order to decide conformance. Realization of the SI definition of the meter can be evaluated in a number of ways, including calibration of the laser IFM, 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 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.

ASME B89.4.19-2021 was approved by ANSI on September 13, 2021.

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| | |
|---|---|
| Subject: | Cite the applicable paragraph number(s) and the topic of the inquiry in one or two words. |
| 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. Please provide a condensed and precise question, composed in such a way that a "yes" or "no" reply is acceptable. |
| Proposed Reply(ies): | Provide a proposed reply(ies) in the form of "Yes" or "No," with explanation as needed. If entering replies to more than one question, please number the questions and replies. |
| Background Information: | Provide the Committee with any background information that will assist the Committee in understanding the inquiry. The Inquirer may also include any plans or drawings that are necessary to explain the question; however, they should not contain proprietary names or information. |

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

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# ASME B89.4.19-2021
# SUMMARY OF CHANGES

Following approval by the ASME B89 Committee and ASME, and after public review, ASME B89.4.19-2021 was approved by the American National Standards Institute on September 13, 2021.

The figures, forms, and tables in ASME B89.4.19-2021 have been redesignated based on their parent paragraphs. ASME B89.4.19-2021 also includes the following changes identified by a margin note, **(21)**.

| *Page* | *Location* | *Change* |
|---|---|---|
| 1 | 1 | Revised |
| 1 | 2 | Revised |
| 2 | 3 | Revised in its entirety |
| 4 | 4 | Revised |
| 5 | Form 4-1 | Title and subheadings revised |
| 6 | Form 4-2 | Title revised |
| 4 | 5 | Revised |
| 4 | 6 | Revised in its entirety |
| 13 | Table 6.3.1-1 | Title revised |
| 18 | 7 | Revised in its entirety |
| 19 | Figure 7.1-1 | Title revised |
| 22 | Figure 7.4.2-1 | Title revised |
| 21 | 8 | References updated |
| 23 | Mandatory Appendix I | Revised in its entirety |
| 25 | Nonmandatory Appendix A | Revised |
| 26 | Table A-2-1 | Revised |
| 27 | B-1 | First sentence and subpara. (a) revised |
| 27 | B-2.1 | Third paragraph revised |
| 27 | B-2.2 | Second and fifth sentences revised |
| 28 | Figure B-2.2-1 | General Note added |
| 29 | B-3 | First, second, ninth, and tenth paragraphs revised |
| 34 | C-4 | Second and fourth paragraphs revised |
| 34 | C-4.1 | First sentence revised |
| 34 | C-5 | First paragraph revised |
| 37 | Nonmandatory Appendix D | Revised in its entirety |
| 49 | E-1 | First sentence revised |
| 55 | Nonmandatory Appendix F | Revised in its entirety |
| 56 | Figure F-5.1.2-1 | Added |
| 57 | Figure F-5.1.2-2 | Added |
| 58 | Figure F-5.2.2-1 | Added |

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# PERFORMANCE EVALUATION OF LASER-BASED SPHERICAL COORDINATE MEASUREMENT SYSTEMS

## 1 SCOPE (21)

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

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

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

## 2 INTRODUCTION (21)

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

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

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

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

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

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

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

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



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

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

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

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

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

Additional tests are included that characterize the consistency of the coordinates of a point when measured in both 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 shall satisfy the traceability requirements of Mandatory Appendix I. The summary test results shall be evaluated using the performance evaluation test procedures of section 7 and reported on Form 4-1.

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

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

## (21) 3 DEFINITIONS

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

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

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

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

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

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

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

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

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

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

NOTES:
(1) The home point serves as a distance reference for the laser tracker's ranging devices.
(2) The home point is also sometimes referred to as the birdbath.

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

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

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

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

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

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

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

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

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

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

NOTES:
(1) Rated operating conditions generally specify intervals of values for a quantity being measured and for any influence quantity.
(2) In this document, rated operating conditions are also referred to as rated conditions.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

## (21) 4 SPECIFICATIONS AND RATED CONDITIONS

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

## (21) 5 TEST ENVIRONMENT

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

## (21) 6 PERFORMANCE EVALUATION TESTS

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

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

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

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

### 6.1 General Requirements

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

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

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## Form 4-1
## Specifications of Rated and Limiting Operating Conditions

(21)

**RATED OPERATING 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 OPERATING 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

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(21)

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

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

Test Performed by:____________________ Date:________________ Instrument Serial Number: ________________

$C_m$ for IFM System Tests:__________ ; $C_m$ for IFM Ranging Tests:__________ if $1 \leq C_m < 2$ Check ☐ "Low_$C_m$"

$C_m$ for ADM System Tests:__________ ; $C_m$ for ADM Ranging Tests:__________ if $1 \leq C_m < 2$ Check ☐ "Low_$C_m$"

Final Test Results (Pass/Fail):__________

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

NOTES:
(1) $\delta$ for length system results, $\Delta$ 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.

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

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

The specific tests that shall be performed for each laser tracker configuration are shown in Table 6.1-1. A system meets the manufacturer's performance specifications if the magnitude of the difference between each measured length and the corresponding reference length does not exceed the specified MPE. This acceptance criterion corresponds to a simple acceptance and rejection decision rule[2] with a stated measurement capability index, $C_m$ (see Nonmandatory Appendix D).

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

## 6.2 Length Measurement System Tests

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

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

*(a)* a calibrated artifact capable of holding retroreflectors near its ends (e.g., a scale bar)

*(b)* two SMR kinematic nests mounted on independent freestanding rigid structures, with the distance between the nests calibrated by a distance or displacement measuring device

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

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

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

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

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

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

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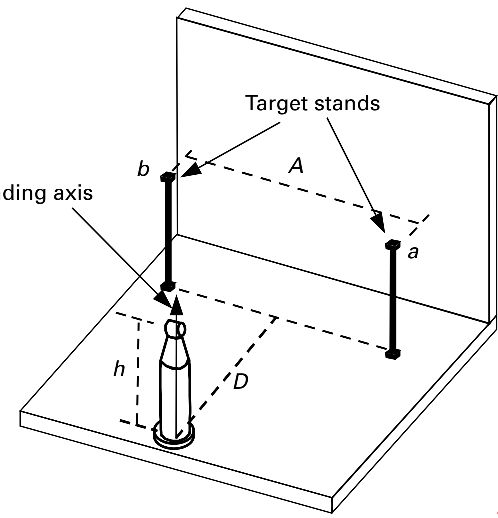
**Table 6.2.1-1**
**Horizontal Length Measurement System Test**




| Position Number | Distance, *D* (Approximate) | Measured Horizontal Angle to Target Nest *a*, deg |
|---|---|---|
| 1 | 0.1*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 |

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

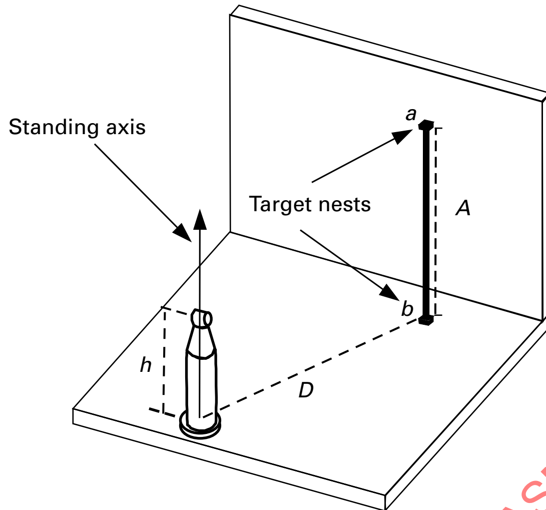
When performing a point-to-point length test, test personnel shall measure both ends of the reference length in the same face of the laser tracker, in either frontsight or backsight mode. Although it is not required that all reference lengths be measured in the same face, it is desirable.

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

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

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

**Table 6.2.1-2**
**Vertical Length Measurement System Test**




| Position Number | Distance, *D* (Approximate) | Measured Horizontal Angle to Target Nests *a* and *b*, deg |
|---|---|---|
| 1 | 1.2*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 |

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

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

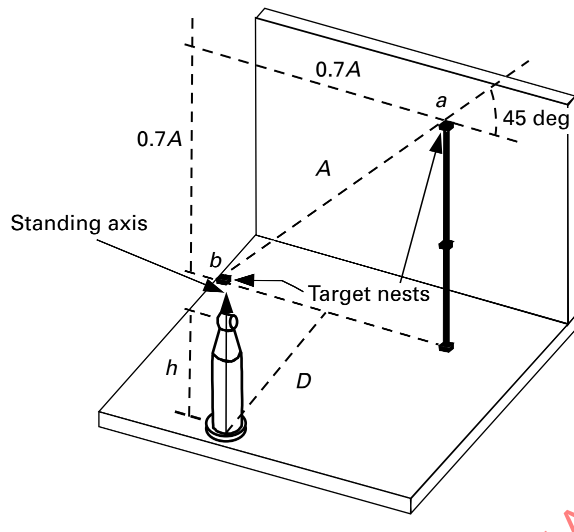
*Step 1.* Examine the reference length or lengths to assess stability and, if necessary, recalibrate the reference length or lengths. This is particularly relevant to para. 6.2.1(b), where drift in the location of the target nests can degrade the reference length.

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

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

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

**Table 6.2.1-3**
**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.

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and the laser tracker. The laser tracker shall be positioned so that it is approximately equidistant from target nests *a* and *b*. Measurements shall be made with the laser tracker positioned and oriented as described in Table 6.2.1-1.

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

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

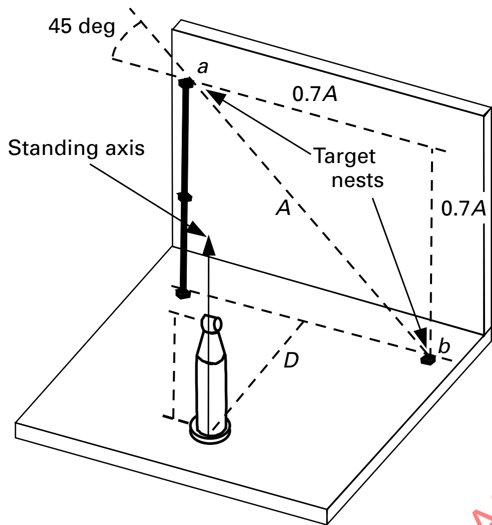
**6.2.5 Vertical Length Measurement System Tests.** A vertical reference length having target nests *a* and *b* is shown in the illustration in Table 6.2.1-2. The distance *A* should be at least 2.3 m in length. The height *h* of the laser tracker should be approximately midway between the heights of nests *a* and *b*. *D* represents the distance between the reference length and the laser tracker. Measurements are made with the laser tracker positioned and oriented as described in Table 6.2.1-2.

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

Three repeat measurements shall be 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 target nests *a* and *b* is shown in the illustration to Table 6.2.1-3. The distance *A* should be at least 2.3 m in length. The height *h* of the laser tracker should be approximately midway between the heights of nests *a* and *b*. *D* represents the distance between the reference length and the laser tracker. The laser tracker shall be positioned so that it is approximately equidistant from the targets at *a* and *b*. Measurements are made with the laser tracker positioned and oriented as described in Table 6.2.1-3.

**Table 6.2.1-4**
**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.

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

Three repeat measurements shall be 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 target nests *a* and *b* is shown in the illustration to Table 6.2.1-4. The distance *A* should be at least 2.3 m in length. The height *h* of the laser tracker should be approximately midway between the heights of nests *a* and *b*. *D* represents the distance between the reference length and the laser tracker. The laser tracker shall be positioned so that it is approximately equidistant from the targets at *a* and *b*. Measurements are made with the laser tracker positioned and oriented as described in Table 6.2.1-4.

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

Three repeat measurements shall be 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 may specify two additional length measurements anywhere in the laser tracker measurement envelope. The following two positions are the recommended default test positions that shall 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, as this position is sensitive to errors in the vertical angle encoder of the laser tracker. The test position is similar to that in the illustration in Table 6.2.1-2, except that the reference length is shifted up vertically such that the lower target nest (denoted as *b* in illustration in Table 6.2.1-2) is approximately at the laser tracker height. The laser tracker should be as close as possible to the reference length (i.e., the distance *D* in the illustration in Table 6.2.1-2 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 in para. 6.2.6, except the reference length is positioned at a compound angle that involves approximately the same 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 away.

The user may specify positions other than the default ones. However, if the specified positions require a reference length other than the length or lengths used for testing in paras. 6.2.4 through 6.2.7 and para. 6.4, 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 System Test Procedure.** The two-face measurement setup is shown in the illustration in Table 6.3.1-1. Three target nests are placed as shown: one below the laser tracker, one at approximately the laser tracker's height, and one at twice the laser tracker's height above the lower target nest. *D* represents the distance between the laser tracker and the target nest on the floor. Measurements are made with the laser tracker positioned as described in Table 6.3.1-1.

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 system under test. In this case, measurements shall be equally distributed and span the entire available angular range.

A two-face system test is performed by measuring a target first in the frontsight mode and then in the backsight mode. For each test position number in Table 6.3.1-1, a two-face system test is performed on each of the three targets in nests *a, b*, and *c*. This test is repeated a total of three times for each target. The largest two-face error from the nine measurements is reported for each test position number in Table 6.3.1-1. Because MPE specifications are generally the same for a group of test positions that are only different because of the physical rotation of the tracker (e.g., test positions 1, 2, 3, and 4 in Table 6.3.1-1), the largest two-face error for each group of test positions is reported in Form 4-2. In Form 4-2, it is assumed that the MPE specification for the three targets in nests *a*, *b*, and *c* are the same for any given test position. If that is not the case, Form 4-2 shall be suitably modified to account for the varying MPEs for the three targets.

It is permissible to perform frontsight mode measurements of the three targets and then perform the backsight mode measurements of the three targets for any given test position number in Table 6.3.1-1. Thus, the measurement sequence may be $a_F b_F c_F – a_B b_B c_B – a_F b_F c_F – a_B b_B c_B – a_F b_F c_F – a_B b_B c_B$, $a_F a_B – b_F b_B – c_F c_B – a_F a_B – b_F b_B – c_F c_B – a_F a_B – b_F b_B – c_F c_B$, or $a_F a_B – a_F a_B – a_F a_B – b_F b_B – b_F b_B – b_F b_B – c_F c_B – c_F c_B – c_F c_B$, where the subscripts *F* and *B* denote frontsight and backsight, respectively. Measurement results are reported as described in section 7.

**6.3.2 Failure to Satisfy MPE Requirements.** There are a total of 12 two-face system test positions. Each position has three targets, thus there are a total of 36 individual target measurements. Each individual target is measured three times, thus there are 108 two-face measurements in all. A maximum of five of the 36 individual target measurements may have two-face errors outside of the conformance zone. No more than one of the three repeat measurements for any individual target may have two-face errors outside of the conformance zone. If the laser tracker fails to meet the specification for more than five measurements or has more than one of the three repeat measurements for an individual target outside the conformance zone, the laser tracker shall be compensated, repaired, or replaced, and the performance evaluation testing shall be repeated. If the laser tracker fails to meet the specification at one to five measurements, 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.* Repeat the two-face measurements of the failed target position five times.

*Step 3.* If the repeat measurements satisfy the MPE requirement, then the laser tracker satisfies the requirements for the measurement at the failed test position, and testing can continue. If the repeat measurements fail 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 evaluation test. The system shall be compensated, repaired, or replaced, and the performance evaluation testing shall be repeated.



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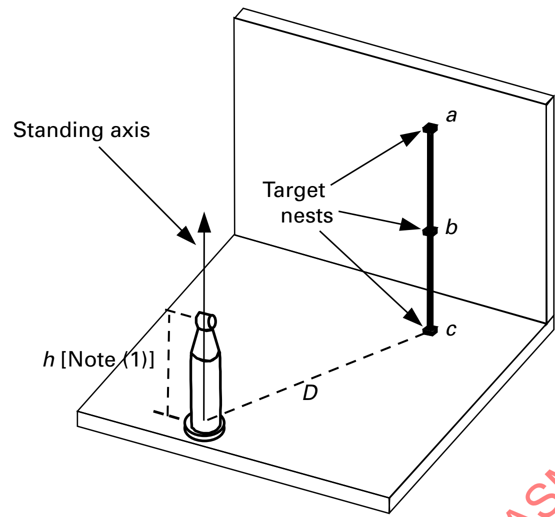
**Table 6.3.1-1**
**Two-Face System Test** (21)




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

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

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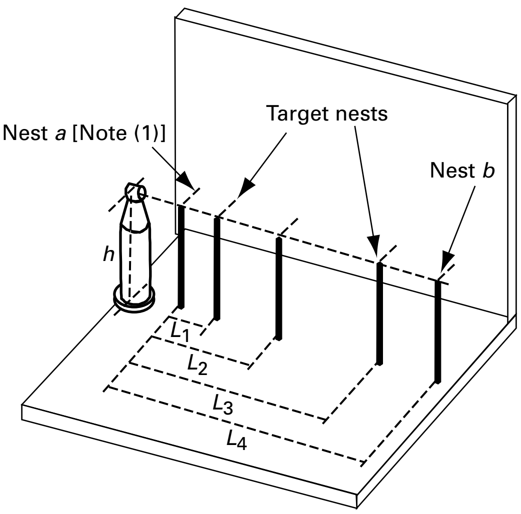
## 6.4 Ranging Tests

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

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

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

**Table 6.4.1-1**
**Ranging Test**




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

NOTES:
(1) The target nest *a* should be 3 m from the laser tracker.
(2) *R* = maximum ranging distance.

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where
$L_{ref}$ = one of the following:
*(a)* a long reference length [see paras. 6.4.2(a), 6.4.3, 6.4.4(a), and 6.4.4(b)] taken from Table 6.4.1-1 (see also Nonmandatory Appendix D, section D-2)
*(b)* a short reference length taken from para. 6.4.2(b)
*(c)* a reference length for laser interferometer calibration [see para. 6.4.2(c)] taken from Table 6.4.1-1

and $U_{k=2}(L_{ref})$ is evaluated as in Nonmandatory Appendix D, para. D-4.1. (Also see para. 7.3 and Mandatory Appendix I.)

Because of the high accuracy (low MPE) of some laser tracker ranging subsystems, 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 4-2, 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.** In the case of IFM testing, there are a total of four long reference length test positions (each measured once) or a total of four short reference length test positions (each measured three times). In the case of ADM testing, there are a total of six long reference length test positions (each measured once). For IFM, a maximum of one out of four test positions may have length error outside of the conformance zone. For ADM, a maximum of one out of six test positions may have length error outside of the conformance zone. If the laser tracker fails to meet the specification for more than one test position, the laser tracker shall be compensated, repaired, or replaced, and the performance evaluation testing shall be repeated. If the laser tracker fails to meet the specification at one test position, the following actions shall be taken:

*(a)* In the case of a long reference length (ADM or IFM)

*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 largest absolute value of the five length errors (length error is the measured length minus the reference length) to replace the failed position value.

*Step 3.* If the new value satisfies the MPE requirement, then the laser tracker satisfies the 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 evaluation test. The system shall be compensated, repaired, or replaced and the performance evaluation testing shall be repeated.

*(b)* In the case of a short reference length (IFM only)

*Step 1.* Examine all four short reference lengths to assess their stability and, if necessary, recalibrate the reference length(s). This is particularly relevant in situations where drift in the location of the target nests can degrade the reference length, such as when using target nests mounted on stands.

*Step 2.* Remeasure all four short reference lengths three times, perform the least-squares fit as described in para. 7.3.1, and determine the errors corresponding to the four long reference test positions in Table 6.4.1-1. Repeat this process five times, and select the largest error from the five repeats for each test position in Table 6.4.1-1.

*Step 3.* If the new values for the four test positions all satisfy the MPE requirement, then the laser tracker satisfies the requirements for that measurement and testing can continue. If at least one of the new values 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 evaluation test. The system shall be repaired or replaced and the performance evaluation testing shall be repeated.

*(c)* In the case that a laser calibration [see para. 6.4.2(c)] is used to evaluate the IFM ranging performance, failure to satisfy the MPE requirements indicates that the IFM is not operating correctly or the laser wavelength calibration is in doubt. The manufacturer shall address the situation as appropriate.

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

*(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 spans a significant portion of the maximum ranging distance. The reference lengths are specified in Table 6.4.1-1, where $R$ is the maximum range of the IFM. No user-selected positions are required for the IFM ranging test. Details regarding realizing the long reference lengths are given in para. 6.4.4. Measurement results are reported as described in section 7.

*(b) Short Reference Lengths.* In this method, 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 are 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. For each of the four reference lengths, the close end of the reference length shall be located at the same distance from the laser tracker. Each of the four lengths is 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). A least-squares best-fit line is fit to the errors as described in para. 7.3.1, and long reference length errors are computed. Measurement results shall be reported as described in section 7.

*(c) Laser Interferometer Calibration.* The IFM in the laser tracker shall be calibrated according to ASME B89.1.8-2011 (R2021). 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 paragraph are designed to test the measurement capability of the ADM ranging subsystem 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 spans a significant portion of the maximum ranging distance. The reference lengths, including two user-selected lengths, are specified in Table 6.4.1-1, where $R$ is the maximum range of the ADM. Details regarding realizing the reference lengths are given in para. 6.4.4. Measurement results are reported as described in section 7.

NOTE: The methods used to test the IFM and ADM are not required to be the same. For example, the IFM might be tested using the laser calibration procedure [see 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).

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**6.4.4 Long Reference Lengths for Ranging Tests.** Long reference lengths for IFM and ADM ranging tests may be realized by either of the following methods:

*(a) Lengths Created Using Rail and Target Carriage.* In the case of ADM ranging tests, if the laser tracker has an IFM that meets the ranging test requirements of para. 6.4.2 and the measurement capability index requirements of para. 6.4.1, the laser tracker may be used to calibrate the ADM reference lengths along the rail. If the laser tracker does not have an IFM, or for testing the laser tracker's IFM, a displacement interferometer may be used.

*(b) SMR 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 of para. 6.4.2, then that IFM may be used to calibrate the reference lengths.

The reference lengths are denoted $L_1$ through $L_4$ in the illustration in Table 6.4.1-1. As depicted in the illustration, a reference length is the length between the target nest closest to the laser tracker (i.e., nest *a*) and each of the subsequent target nests. Target nest *a* should be placed 3 m from the laser tracker. The nests collinear with those labeled *a* and *b* shall be along the radial direction of and at approximately the height, *h*, of the laser tracker.

A single measurement consists of measuring the distance to each of the target nests in sequence. These distances are then used to calculate the lengths depicted in the illustration in Table 6.4.1-1.

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 6.4.1-1.

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 using eq. (1).

Lengths *A* and *B* in Figure 6.4.4.1-1 represent the laser tracker range measurements (i.e., distances from the laser tracker origin) 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 magnitude of the cosine error is then

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

The misalignment of the laser tracker can be determined by either measuring its physical offset from the reference line, labeled *C* in Figure 6.4.4.1-1, or by recording the change in angle $\theta$ between the two measurement points that comprise a measured length (see Figure 6.4.4.1-1). The angle $\theta$ 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, $\theta$ can be estimated by

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

where $\Delta H$ and $\Delta V$ are the changes in the horizontal and vertical angles, in radians, between the two points that define a reference length.

Once nominal values for the lengths *A* and *B* are known, the cosine error $\Delta L$ can be calculated given either the offset *C* or the angle $\theta$, using one of the following equations:

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

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

Figure 6.4.4.1-2 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, for example, 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 subsystems. The cosine error calculation is important during the alignment of the laser tracker with the points *a* and *b* shown in Figure 6.4.4.1-1. After the tracker is aligned, the distance between the points *a* and *b* is determined using three-dimensional coordinates, not just the range measurement.

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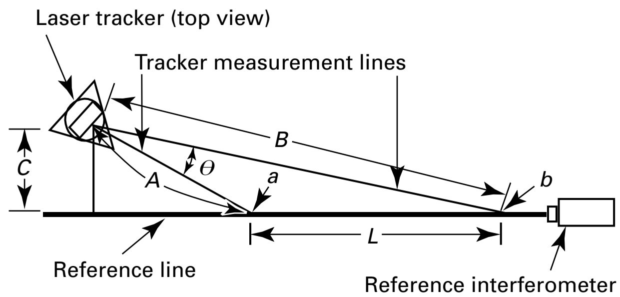
**Figure 6.4.4.1-1**
**Laser Tracker and Reference Interferometer Alignment**




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

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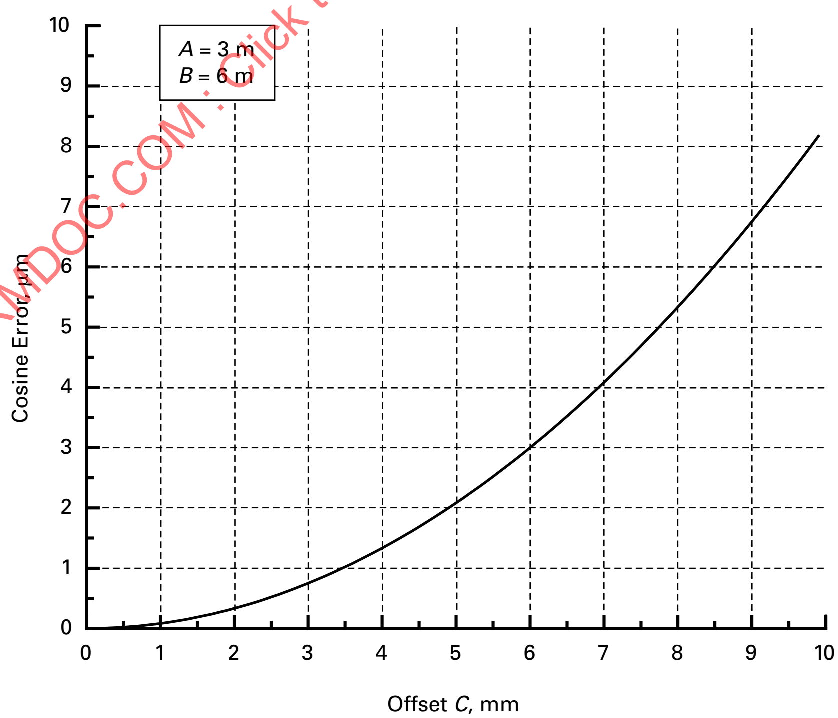
**Figure 6.4.4.1-2**
**Cosine Error Versus Offset *C* From Reference Line**




GENERAL NOTE: In this example, $A$ = 3 m and $B$ = 6 m (see Figure 6.4.4.1-1).

## (21) 7 ANALYSIS OF PERFORMANCE EVALUATION TESTS

### 7.1 Evaluation of Length Measurement System Tests of Para. 6.2

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

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

where

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

There are three values ($\delta_1$, $\delta_2$, and $\delta_3$) 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 6.2.1-1). For a group of test positions, a single MPE is specified and the largest value of $\delta_{\max}$ is reported on Form 4-2 (see example in Figure 7.1-1).

### 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 target nest location, the measured target position in frontsight mode is a point $P_F$ with coordinates ($x_F$, $y_F$, and $z_F$). In backsight mode, the measured position is a point $P_B$ with coordinates ($x_B$, $y_B$, and $z_B$). The distance between these points is the apparent separation, $\Delta$, as calculated by the laser tracker software. There are three separations ($\Delta_{1a}$, $\Delta_{2a}$, and $\Delta_{3a}$) for target nest location $a$ corresponding to the three repeated measurements. Likewise, there are three separations for target nest locations $b$ and $c$ ($\Delta_{1b}$, $\Delta_{2b}$, $\Delta_{3b}$, $\Delta_{1c}$, $\Delta_{2c}$, and $\Delta_{3c}$). The test of conformance for each test position in Table 6.3.1-1 requires comparing the largest value, $\Delta_{\max}$ = max ($\Delta_{1a}$, $\Delta_{2a}$, $\Delta_{3a}$, $\Delta_{1b}$, $\Delta_{2b}$, $\Delta_{3b}$, $\Delta_{1c}$, $\Delta_{2c}$, $\Delta_{3c}$), with the corresponding MPE specification, i.e., $\Delta_{\max} \leq$ MPE (see the examples in para. 7.4).

Form 4-2 shows two-face system tests combined together in groups differing only in the orientation of the laser tracker [e.g., two-face system test positions 1, 2, 3, and 4 (see Table 6.3.1-1)]. When grouped together in that manner, a single MPE is specified for a group, and the largest value of $\Delta_{\max}$ is reported on Form 4-2 (see example shown in Figure 7.1-1). As mentioned in para. 6.3.1, this method of grouping two-face system tests is valid when the MPE specification for the three targets, *a, b*, and *c,* are the same for a given test position. If that is not the case, Form 4-2 shall be suitably modified.

### 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 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
$L_{\mathrm{ref}}$ = reference length

The test of conformance for each measured point-to-point length error requires comparing the value of $\delta$ with the corresponding MPE specification for that length, i.e., $|\delta| \leq$ MPE for all lengths $\delta$ (see the example in Figure 7.1-1).

For the case of short reference lengths, the difference between the measured length and the short reference length shall be calculated using eq. (7) for each of the 12 measured short reference lengths.

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

A least-squares line fit of the form $A + BL$ shall be performed through all 12 values of $\varepsilon$ and the corresponding slope and intercept shall be determined where $A$ and $B$ (not to be confused with $A$ and $B$ in para. 6.4.4.1) are computed from the least-squares fit (see Figure 7.3.1-1). Four values of $\delta$ are computed by using the following equation:

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

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

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

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

Test Performed by: Jones    Date: 3/18/2021    Instrument Serial Number: 1234

$C_m$ for IFM System Tests: 5.2 ;    $C_m$ for IFM Ranging Tests: 2.5    if $1 \le C_m < 2$ Check ☐ "Low_$C_m$"

$C_m$ for ADM System Tests: 6 ;    $C_m$ for ADM Ranging Tests: 2.1    if $1 \le C_m < 2$ Check ☐ "Low_$C_m$"

Final Test Results (Pass/Fail): Fail

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

NOTES:
(1) $\delta$ for length system results, $\Delta$ 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.

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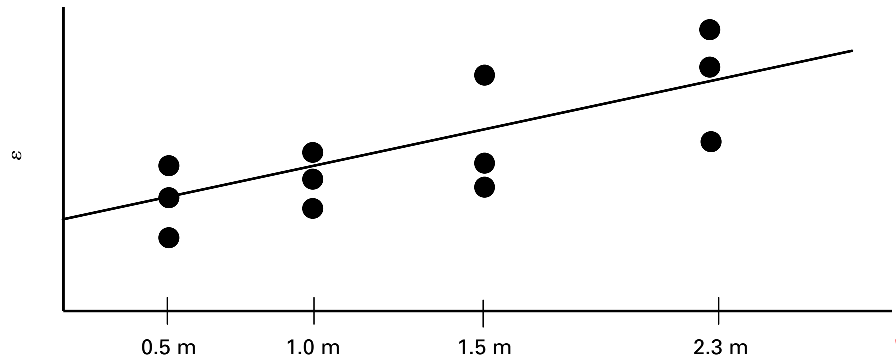
**Figure 7.3.1-1**
**Least-Squares Line Fit to 12 Short Reference Lengths**




where the $L_{\text{ref}}$s are the four long reference lengths specified in Table 6.4.1-1. The test of conformance for each computed length error requires comparing the value $\delta$ with the corresponding MPE specification for that length, i.e., $|\delta| \le$ MPE for all four long lengths given in Table 6.4.1-1 (see the examples in para. 7.4).

For the case of the laser IFM calibration method described in para 6.4.2(c), four values of $\delta$ are computed by the following equation:

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

where the $L_{\text{ref}}$s are the four lengths specified in Table 6.4.1-1, 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 $\delta$ with the corresponding MPE specification for that length, i.e., $|\delta| \le$ MPE for all four lengths given in Table 6.4.1-1 (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).

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

where

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

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

## 7.4 Examples of Failure to Satisfy MPE Requirements

If the absolute value of any length difference, $\delta$, or any apparent separation, $\Delta$, 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, para. 6.3.2, or para. 6.4.1.1, as appropriate, shall be followed, and if the system still fails to meet the manufacturer's performance specifications, then it shall be repaired or replaced before the performance evaluation testing is resumed.

**7.4.1 Example of Default Test Method.** Figure 7.1-1 shows the test data for a laser tracker tested using the default method from Table 6.1-1. The laser tracker had both an ADM and an integrally mounted IFM.

In Figure 7.1-1, the maximum error in position 5, 6, 7, or 8 for the vertical length measurement system test and the maximum error in position 2, 3, 4, or 5 for the horizontal length measurement system test exceed the MPEs for the IFM and ADM, respectively (these values are from the second retest, per para. 6.2.3). As a consequence, the laser tracker fails to meet the manufacturer's performance specifications.

**7.4.2 Example of Alternative Test Method.** Figure 7.4.2-1 shows the test data for a laser tracker tested using the alternative method from Table 6.1-1. The laser tracker had both an ADM and an integrally mounted IFM. The manufacturer's MPE(s) are shown together with the measurement results from the ADM and the required IFM measurements.

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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 Figure 7.4.2-1, the maximum error in position 5, 6, 7, or 8 for the vertical length measurement system test and the maximum error in position 2, 3, 4, or 5 for the horizontal length measurement system test exceed the MPEs for the IFM and ADM, respectively. As a consequence, the system fails to meet the manufacturer's performance specifications.

## 8 REFERENCES (21)

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

ASME B89.1.8-2011 (R2021), Performance Evaluation of Displacement Measuring Laser Interferometers
ASME B89.6.2-1973 (R2017), Temperature and Humidity Environment for Dimensional Measurement
ASME B89.7.3.1-2001 (R2019), Guidelines for Decision Rules: Considering Measurement Uncertainty in Determining Conformance to Specifications
ASME B89.7.5-2006 (R2016), Metrological Traceability of Dimensional Measurements to the SI Unit of Length
ASME B89.7.6-2019, Guidelines for the Evaluation of Uncertainty of Test Values Associated With the Verification of Dimensional Measuring Instruments to Their Performance Specifications
Publisher: The American Society of Mechanical Engineers (ASME), Two Park Avenue, New York, NY 10016-5990 (www.asme.org)

Ciddor, P. E. (1996), "Refractive Index of Air: New Equations for the Visible and Near Infrared," *Applied Optics,* Vol. 35, 1566–1573.
Ciddor, P. E., and Hill, R. J. (1999), "Refractive Index of Air: 2. Group Index," *Applied Optics*, Vol. 38, 1663–1667
Publisher: Optica Publishing Group [formerly Optical Society of America (OSA) Publishing], 2010 Massachusetts Avenue, NW, Washington, DC 20036-1012 (www.opg.optica.org)

ISO 1:2016, Geometrical product specifications (GPS) — Standard reference temperature for the specification of geometrical and dimensional properties
ISO/IEC 17025:2017, General requirements for the competence of testing and calibration laboratories
JCGM 200:2012, International Vocabulary of Metrology—Basic and General Concepts and Associated Terms, Third Edition (VIM3)
Publisher: International Organization for Standardization (ISO), Central Secretariat, Chemin de Blandonnet 8, Case Postale 401, 1214 Vernier, Geneva, Switzerland (www.iso.org)

Rüeger, J. M. (1996), *Electronic Distance Measurement: An Introduction,* Fourth Edition
Publisher: Springer, Berlin; contact: Springer Nature, One New York Plaza, Suite 4600, New York, NY 10004-1562 (www.springer.com)

Stone, J. A., and Zimmerman, J. H., "Refractive Index of Air Calculator," The National Institute of Standards and Technology (NIST), last modified July 1, 2019, https://emtoolbox.nist.gov/Wavelength/Abstract.asp

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(21)

## Figure 7.4.2-1
## Form 4-2 With Example Alternative Method Data

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

| Test (Positions) | IFM Specifications and Test Results | | | ADM Specifications and Test Results | | |
|---|---|---|---|---|---|---|
| | $MPE_{IFM}$ | $\delta_{max}$ or $\Delta_{max}$ [Note (1)] | Pass | $MPE_{ADM}$ | $\delta_{max}$ or $\Delta_{max}$ [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 | 16.0 [Note (3)] | Y | | | |
| IFM Ranging Ref $L$ (2) = 18 m | 40 | 31.0 [Note (3)] | Y | | | |
| IFM Ranging Ref $L$ (3) = 27 m | 60 | 48.0 [Note (3)] | Y | | | |
| IFM Ranging Ref $L$ (4) = 36 m | 80 | 61.0 [Note (3)] | Y | | | |
| ADM Ranging Ref $L$ (1) = 9 m | | | | 25 | 13.5 | Y |
| ADM Ranging Ref $L$ (2) = 18 m | | | | 50 | 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: 3/18/2021 Instrument Serial Number: 1234

$C_m$ for IFM System Tests: 5.2 ; $C_m$ for IFM Ranging Tests: 2.5 if $1 \leq C_m < 2$ Check ☐ "Low_$C_m$"

$C_m$ for ADM System Tests: 6 ; $C_m$ for ADM Ranging Tests: 2.1 if $1 \leq C_m < 2$ Check ☐ "Low_$C_m$"

Final Test Results (Pass/Fail): Fail

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

NOTES:
(1) $\delta$ for length system results, $\Delta$ 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.

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# MANDATORY APPENDIX I REFERENCE LENGTH TRACEABILITY

(21)

## I-1 GENERAL TRACEABILITY ISSUES

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

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

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

## I-2 REFERENCE LENGTH TRACEABILITY

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

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

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

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

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

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

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

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

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## 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 in the testing.

*(b)* calibration report from a competent[2] laboratory fulfilling ISO 17025, section 6.5 for the reference length used in the testing.

*(c)* documentation describing an independent realization of the SI definition of the 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., evidence of participation in a round robin or comparison against another independently calibrated length standard).

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

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

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

# NONMANDATORY APPENDIX A TRACEABILITY OF SUBSEQUENT MEASUREMENTS (21)

## A-1 INTRODUCTION

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

## A-2 METROLOGICAL TRACEABILITY EXAMPLE

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

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

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

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

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

*(c)* a statement of the expanded ($k$ = 2) uncertainty associated with the result of the measurement [e.g., $U$ = 11.6 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)].

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

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

If uniform probability distributions are assigned to all input quantities (uncertainty components), 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-2-1.

*(e)* documentary evidence of the traceability of the length standard(s) used in the measurement. There are several ways of doing this, 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 ASME 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 ASME B89.1.8 laser interferometer calibration, and the IFM 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 IFM, bearing the logo of the accreditation agency, is sufficient evidence of documentation traceability.

*(f)* a description of an internal quality assurance program that is used to ensure 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 the measurements are performed within the stated conditions, e.g., from 20°C to 30°C.

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(21)

## Table A-2-1 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 × $\left(22\frac{\mu m}{m°C}\right)$ × $L$ × 0.58 = 0 µm + 6.4$L$ µm |
| CTE | $\left(2\frac{\mu m}{m°C}\right)$ × $L$ × 10°C × 0.58 = 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 |

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

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# NONMANDATORY APPENDIX B
# SPHERICALLY MOUNTED RETROREFLECTOR (SMR) TESTS

## B-1 INTRODUCTION (21)

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

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

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

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## B-2 DETERMINING CENTERING ERROR OF VERTEX OF SMR

### B-2.1 Lateral Centering (21)

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

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

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

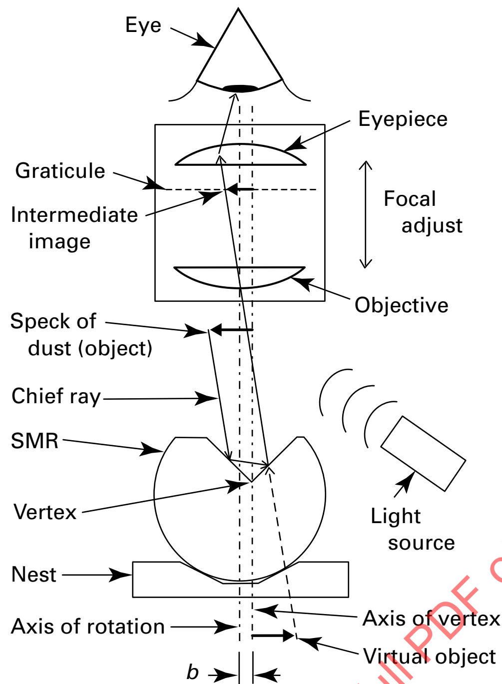
### B-2.2 Radial Centering (21)

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

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

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

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

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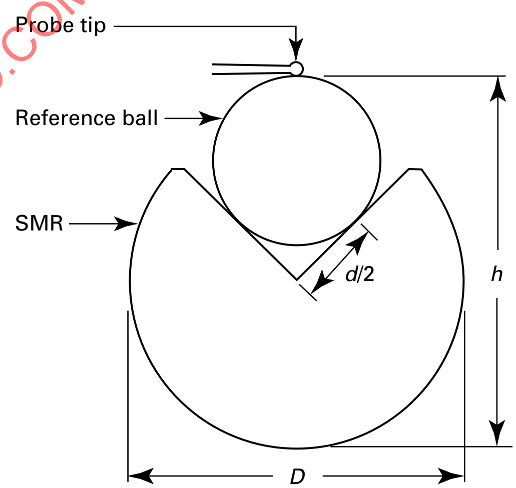
(21)

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




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

## B-3 DIHEDRAL-ANGLE ERRORS (21)

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

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

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

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

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

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

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

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

Now suppose that the wrong control point has been chosen for the PSD. As shown in Figure B-3-2, the incoming and outgoing laser beams do not coincide. For the case shown in Figure B-3-6, the center of the incident laser beam is right of the vertex, and the center of the reflected laser beam is an equal distance left of the vertex. It follows that more of the optical power impinges on segment B and reflects off segment E than impinges on E and reflects off B. If the rays from E bend left by 1 arcsecond and the rays from B bend right by 1 arcsecond, then the left-bending rays will dominate. The reflected beam then strikes the PSD off the control point, causing the servo subsystem of the laser tracker to redirect the 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 their rims, 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 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 (i.e., 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 Figure B-3-7.

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

## B-4 POLARIZATION EFFECTS

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

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

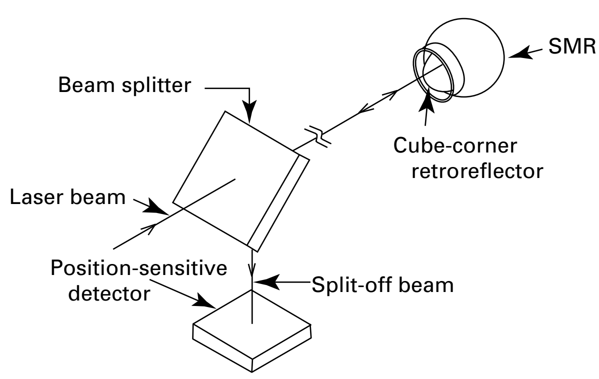


**Figure B-3-2**
**Laser Path With Unintended Offset Between Incoming and Outgoing Beams**

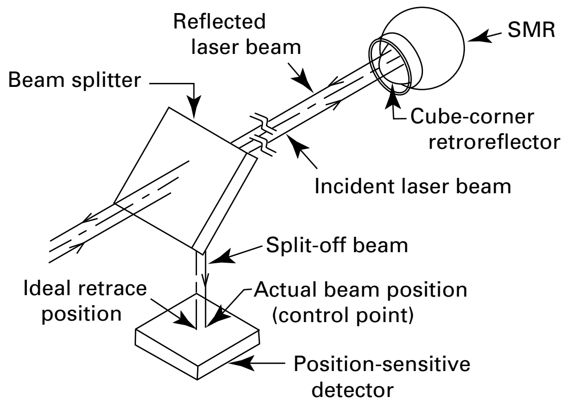
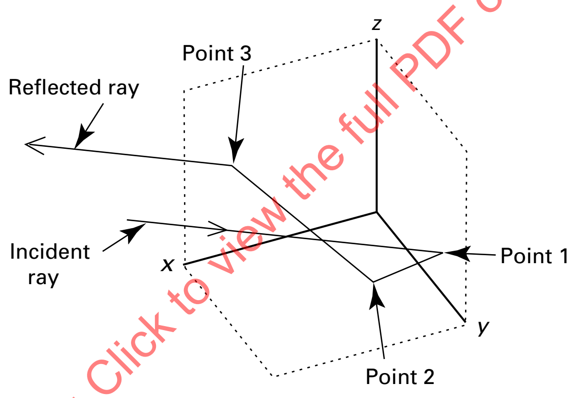



**Figure B-3-3**
**Path of Laser Beam in Cube-Corner Retroreflector**




**Three Mutually Perpendicular Mirrors**

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

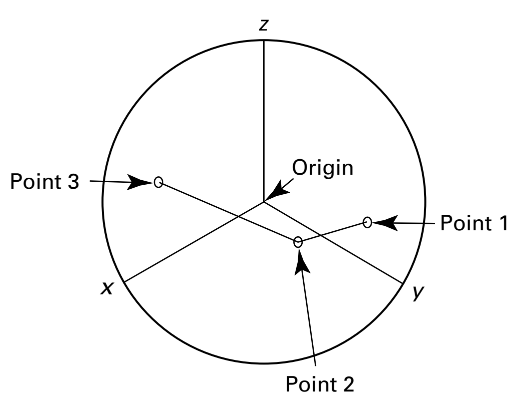



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**Figure B-3-5**
**Top View of Cube Corner With Extended Lines of Intersection**

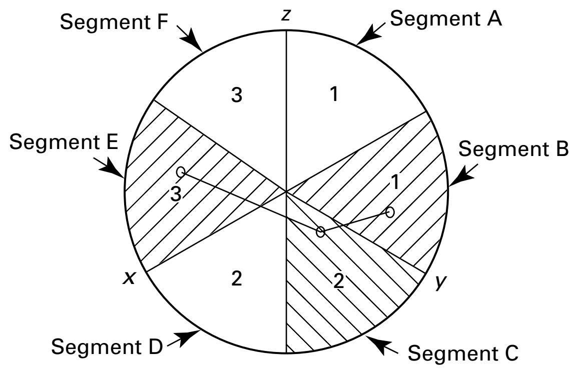



**Figure B-3-6**
**Laser Beams Superimposed on Top View of Dihedral Prism**

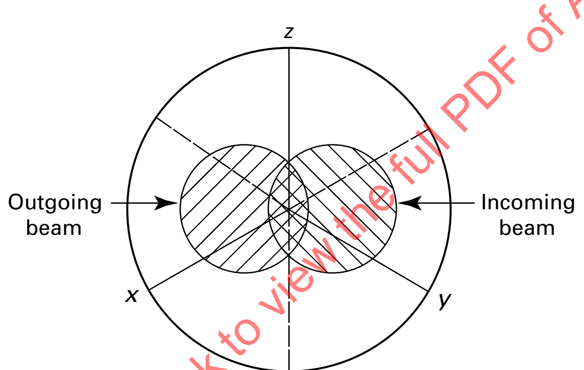
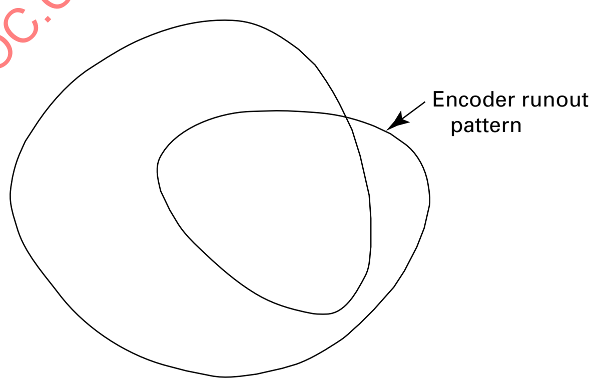



**Figure B-3-7**
**Encoder Runout Pattern**

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# 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 displacement interferometer ranging system (IFM). The manufacturer should have accounted for the effects described in this Appendix in establishing the rated conditions of section 4.

## C-2 PHASE REFRACTIVE INDEX

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

$$n = \frac{c_0}{c} \quad \text{(C-1)}$$

where

$c$ = velocity of light in a medium (i.e., phase velocity)
$c_0$ = velocity of light in vacuum
$n$ = phase refractive index

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 laser tracker with an IFM operating in air, $\lambda_{air}$, is

$$\lambda_{air} = \frac{\lambda_0}{n} \quad \text{(C-2)}$$

where

$n$ = phase refractive index of the air
$\lambda_0$ = vacuum wavelength

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, $n_g$, is defined by

$$n_g = n - \lambda \frac{dn}{d\lambda} \quad \text{(C-3)}$$

where

$\lambda$ = 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] From Rüeger (1996).

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

In addition to its dependence on wavelength, the refractive index of air depends primarily on air pressure, temperature, humidity, and carbon dioxide concentration. Several equations have been proposed to calculate the refractive index, given values of wavelength and environmental parameters. The equations from Ciddor[2] and Ciddor and Hill[3] are recommended for use with this Standard. These equations are valid over a wide range of wavelengths (300 nm to 1 690 nm), temperatures (−20°C to 100°C), pressures (800 hPa to 1 200 hPa), and humidities (0% to 100%).

The National Institute of Standards and Technology (NIST) maintains a web-based tool for calculating the refractive index of air and wavelength of light in air using the Ciddor equation, given values of various input parameters.[4] For exact values of the input parameters, the uncertainties in calculated values of the refractive index are a few parts in $10^8$, only required for the highest level of length metrology.

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

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

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

Most commercial laser trackers use HeNe displacement interferometers, operating at wavelength $\lambda \approx 633$ nm, to realize their IFM ranging subsystems. For such IFMs, and for levels of uncertainty required in laser tracker performance evaluation, a simplified equation[4] can be used to calculate the refractive index of air.

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

where
- $P$ = air pressure, kPa (101.325 kPa = 760 mmHg)
- $RH$ = relative humidity, % (0% ≤ $RH$ ≤ 100%)
- $T$ = air temperature, °C

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

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

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

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

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

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

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

[2] From Ciddor (1996).
[3] From Ciddor and Hill (1999).
[4] From Stone and Zimmerman, "Refractive Index of Air Calculator."

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

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

$$L_m = \frac{L_{\text{vac}}}{n} \tag{C-8}$$

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

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

and since $n \approx 1$,

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

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

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

Figure C-5-1 shows the change in phase refractivity $(n - 1)$ and group refractivity $(n_g - 1)$, for standard dry air, versus wavelength. Standard dry air is defined by Ciddor[2] to be air at 15°C, 1 013.25 hPa, and 0.045% $CO_2$ content with 0% humidity.

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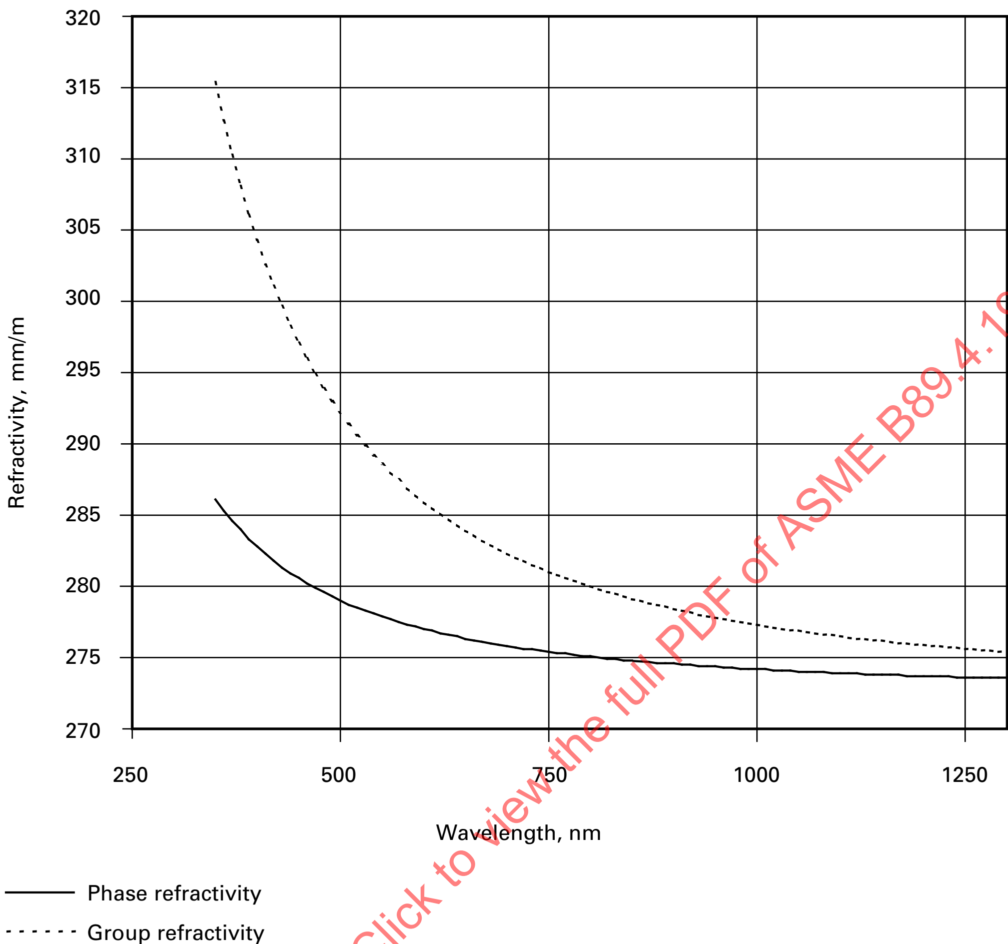
**Figure C-5-1**
**Refractivity for Standard Dry Air**




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

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# NONMANDATORY APPENDIX D REFERENCE LENGTHS FOR LASER TRACKER SYSTEM TESTS AND TEST VALUE UNCERTAINTY (21)

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## D-1 INTRODUCTION

The laser tracker system performance evaluation tests in this Standard include measuring several reference lengths at a prescribed set of locations and orientations within the system's working volume (see para. 6.2).

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

*(a)* section D-3: a calibrated scale bar

*(b)* section D-4: two spherically mounted retroreflectors (SMRs) in kinematic nests calibrated using an interferometer (IFM)

*(c)* section D-5: two SMRs in kinematic nests calibrated using an absolute distance meter (ADM)

*(d)* section D-6: a laser rail system

The test value for a point-to-point length measurement test is the error in the measured length, given as the difference between the length determined by the laser tracker and the calibrated value of that length. The test value is then compared against the maximum permissible error (MPE) specification provided by the manufacturer. The laser tracker has passed the test if

– the test value is smaller than the MPE.

– the test conditions meet the rated operating conditions specified as part of the MPE.

– the $k = 2$ expanded uncertainty in the test value is at least four times smaller than the MPE, which is a requirement of the 4:1 simple acceptance decision rule (see ASME B89.7.3.1). Note that this 4:1 rule applies to point-to-point length tests (see para. 6.2).

Note that the test value is the observed error in the measured value of the reference length at the instant in time the test is performed. If the calibration of the reference length is performed prior to or after the test, drift in the reference length will contribute to the test value uncertainty.

This Appendix discusses four methods to realize the reference length with particular emphasis placed on evaluating the uncertainty in the test value. If that uncertainty is too large, conformance or nonconformance cannot be decided using the default decision rules of this Standard. In the examples herein, it is assumed that the uncertainty arising from the reference length is the only component of the test value uncertainty. This is because this Standard does not involve corrections to the indicated value (i.e., testing is performed within the rated operating conditions and there are no other corrections imposed by this test protocol). See ASME B89.7.6 for more information on test value uncertainty.

## D-2 DECISION RULE FOR DECIDING CONFORMANCE WITH MPE SPECIFICATION

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

$$\delta = L_{\mathrm{m}} - L_{\mathrm{ref}} \tag{D-1}$$

The value of $\delta$ is compared with the manufacturer's 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 that, a test result is accepted if $|\delta| \leq \mathrm{MPE}$, and rejected otherwise, provided that $U_{k=2}(\delta) \leq \mathrm{MPE}/4$, or equivalently, provided that $C_m \geq 4$, where $C_m$ is the measurement capability index, defined by

$$C_m = \frac{\mathrm{MPE}}{2u(\delta)} = \frac{\mathrm{MPE}}{U} \tag{D-2}$$

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

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

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

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

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

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

## D-3 REFERENCE LENGTH REALIZED USING A CALIBRATED SCALE BAR

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

### D-3.1 Uncertainty in the Calibration

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

### D-3.2 Temperature Dependence of Reference Length

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

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

where $\alpha$ is the coefficient of thermal expansion (CTE) of the scale bar.[1]

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

$$u_{CTE}(L_{ref}) = L^0_{ref}\left|T - T_0\right|u(\alpha) \tag{D-6}$$

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

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

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

### D-3.3 Effect of Drift

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

### D-3.4 Orientation of the Scale Bar

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

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

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

### D-3.5 Effect of Mounting

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

### D-3.6 Spherically Mounted Retroreflector (SMR)

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

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

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

### D-3.7 Combined Standard Uncertainty

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

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

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

### D-3.8 Example

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

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

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

When the performance evaluation test is performed on the shop floor, the average temperature of the scale bar is estimated to be 25°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 shop floor environment conforms to the rated operating conditions of the laser tracker. Other sources of uncertainty discussed in paras. D.3.3 through D.3.6 are considered to be negligible in this example.

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

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

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

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

The required uncertainty components are evaluated as follows:

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

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

$$u(T) = (0.5°\text{C})/\sqrt{3}$$

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

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

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

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

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

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

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

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

Thus the measurement capability index is

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

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

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

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

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

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

Since $|\delta|$ is less than the stated MPE of 60 µm, and since $C_m > 4$, the decision rule outcome is "acceptance" that the laser tracker meets the manufacturer's MPE specification for this test.

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

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

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

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

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

### D-4.1 Reference Length Calibration Uncertainty

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

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

*(b) Based on the IFM Uncertainty Tested by a Set of Reference Lengths.* If the IFM is tested using a set of separately calibrated reference lengths, the uncertainty of a measured reference length, $L_{\rm ref}$, 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, $L_1, \ldots, L_N$ (provided $N$ is not small), yields a corresponding set of observed errors, $E_1, \ldots, E_N$. The relative errors (i.e., 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, $r_{\rm max} = \max(r_k)$, is a reasonable estimate of the maximum relative error that might occur when measuring an unknown reference length, $L_{\rm ref}$. This maximum error is then estimated by $e_{\rm ref} = (r_{\rm max})(L_{\rm ref})$, and assigning a uniform distribution of width, $2(r_{\rm ref})(L_{\rm ref})$, yields a standard uncertainty of $u_{\rm cal}(L^0_{\rm ref}) = (r_{\rm max})(L_{\rm ref})/\sqrt{3}$.

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

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

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

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

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

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

$$L^0_{ref} = L_m(1 - c_P\Delta P - c_T\Delta T) \tag{D-9}$$

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

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

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

In the case where the signs of the differences $\Delta P$ and $\Delta T$ are unknown, the best estimates of these quantities are taken to be zero, so that, from eq. (D-9), the best estimate of the reference value is

$$\left(L^0_{ref}\right)_{est} = L_m \tag{D-10}$$

The standard uncertainty $u_{cal}(L^0_{ref})$ associated with the best estimate is computed using the law of propagation of uncertainty (see eq. D-11).

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

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

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

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

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

and

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

The standard calibration uncertainty of the reference length is then

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

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

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

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

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

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

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

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

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

### D-4.3 Other Contributors to Uncertainty in the Reference Length

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

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

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

### D-4.4 Example

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

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

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

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

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

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

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

Then, per section D-2, the measurement capability index is

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

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

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

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

### D-5.1 Reference Length Uncertainty

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

### D-5.2 Other Contributors to Uncertainty in the Reference Length

Uncertainty contributors described in paras. D-4.2 and D-4.3 may also apply in this case.

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

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

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

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

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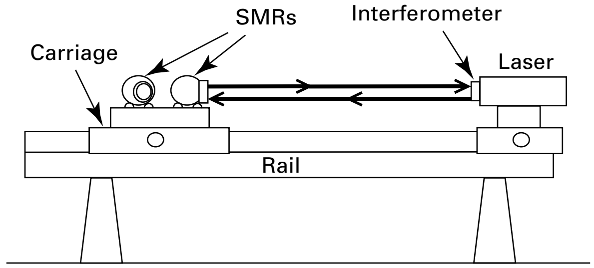
**Figure D-6-1**
**Schematic of Laser Rail System**

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## D-6.1 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 the 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 $1 \times 10^{-6}$, and this error decreases rapidly (for a given beam spot shift) as the carriage travel length increases.

## D-6.2 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.[5] 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. When multiplied by the orthogonal offset distance (known as the Abbé offset), this change in angular orientation 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 component 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 Figure D-6.2-1, illustration (a). The second component 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 Figure D-6.2-1, illustration (b). To estimate the magnitude of the Abbé error, $\varepsilon_{\text{Abbé}}$, these two components are added in quadrature, so that

$$\varepsilon_{\text{Abbé}} = \sqrt{\varepsilon_1^2 + \varepsilon_2^2} \tag{D-18}$$

where

$\varepsilon_1$ = vertical component of the Abbé error
$\varepsilon_2$ = horizontal component of the Abbé error

The magnitude of these errors can be estimated using the chart in Figure D-6.2-2, where the Abbé error is calculated as the product of the Abbé offset and the changes in the pitch or yaw angle.

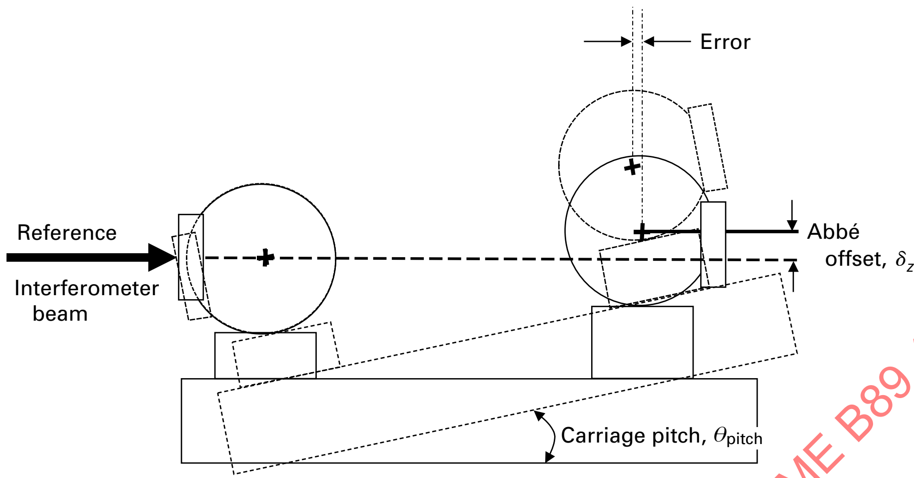
The standard uncertainty associated with the Abbé error can be evaluated by

$$u_{\text{Abbé}}(L_{\text{ref}}) = \frac{\varepsilon_{\text{Abbé}}}{\sqrt{3}} \tag{D-19}$$

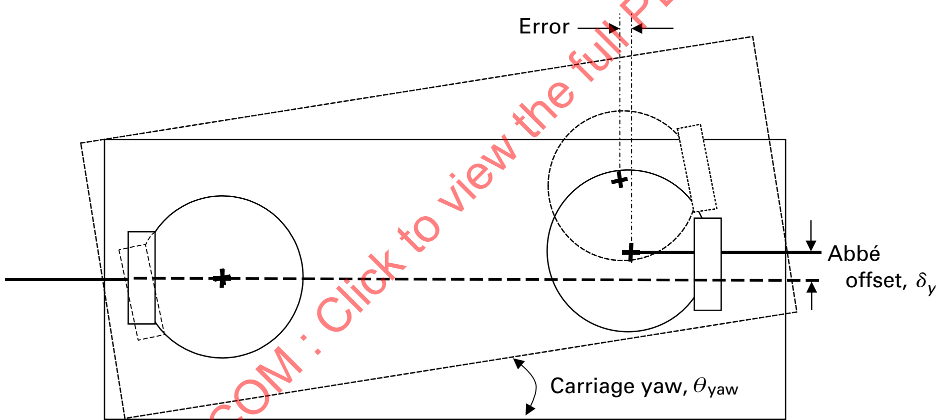
EXAMPLE: The change in pitch and yaw, without regard to sign, of the target carriage at the two points that define the reference length are 60 arcseconds and 70 arcseconds, respectively. The Abbé offset in the vertical and horizontal directions are 5 mm and 4 mm, respectively. From this information, the components of the Abbé error can be estimated from Figure D-6.2-2. The chart gives $\varepsilon_1 \approx \varepsilon_2 \approx 1.4$

[5] 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.

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




**(a) Side View**




**(b) Top View**

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

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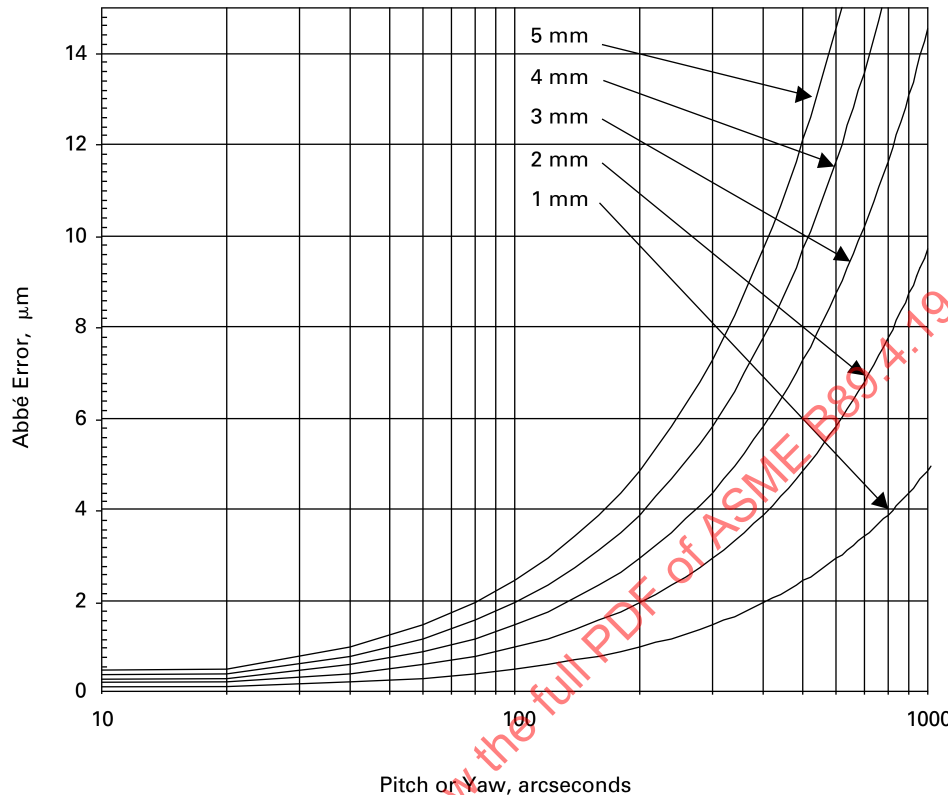
**Figure D-6.2-2**
**Abbé Error Versus Carriage Angular Motion for Various Values of Abbé Offset**




μm. Then, using eqs. (D-18) and (D-19), the magnitude of the expected error is approximately 2.0 μm, and the associated standard uncertainty is approximately 1.2 μm.

## D-6.3 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 associated with the correction for atmospheric conditions. Follow the procedure described in para. D-4.1(d) 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-6.4 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. This will result in the laser tracker and reference length measurements not agreeing. An indicator referenced to the floor and indicating the location of the rail can detect motion of the entire rail system. Typically, rail stability can be made a negligible source of uncertainty.

## D-6.5 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. Since the laser tracker measurement and the calibration of the reference length happen simultaneously, there is no temperature difference to consider between calibration and usage, thus $L_{ref} = L_{ref}^0$. The other uncertainty sources identified in paras. D-3.2 through D-3.6 are

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also zero or negligible. Thus, assuming negligible cosine and rail stability uncertainty components, the combined standard uncertainty, $u(L_{\text{ref}})$, is given by

$$\begin{aligned} u(L_{\text{ref}}) &= u_{\text{cal}}(L^0_{\text{ref}}) \\ &= \sqrt{L_m^2\left(\frac{c_P^2\,|\Delta P|^2_{\max}}{3} + \frac{c_T^2\,|\Delta T|^2_{\max}}{3}\right) + u^2_{\text{Abbé}}(L_{\text{ref}})} \end{aligned} \quad \text{(D-20)}$$

where $c_P$ and $c_T$ are described in para. D-4.1 and in Nonmandatory Appendix C, and $u_{\text{Abbé}}(L_{\text{ref}})$ is described by eq. (D-19).

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