भारतीय मानक

Indian Standard

IS 15635 (Part 10) : 2023
ISO 10360-10: 2021

ज्यामितीय उत्पाद विशिष्टि (जी.पी.एस.) — संयोजी मापन प्रणाली (सी.एम.एस.) की स्वीकार्यता और पुनर्जांच परीक्षण

भाग 10 लेज़र ट्रैकर्स

Geometrical Product Specifications (GPS) — Acceptance and Reverification Tests for Coordinate Measuring Systems (CMS)

Part 10 Laser Trackers

ICS 17.040.30

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NATIONAL FOREWORD

This Indian Standard (Part 10) which is identical with ISO 10360-10 : 2021 'Geometrical product specifications (GPS) — Acceptance and reverification tests for coordinate measuring systems (CMS) — Part 10: Laser trackers' issued by the International Organization for Standardization (ISO) was adopted by the Bureau of Indian Standards on recommendation of the Engineering Metrology Sectional Committee and approval of the Production and General Engineering Division Council.

Laser trackers are coordinate measuring system in which a cooperative target is followed with a laser beam and its location determined in terms of a distance (range) and two angles.

The text of ISO Standard has been approved as suitable for publication as an Indian Standard without deviations. Certain conventions are, however, not identical to those used in Indian Standards. Attention is particularly drawn to the following:

a) Wherever the words 'International Standard' appear referring to this standard, they should be read as 'Indian Standard'.
b) Comma (,) has been used as a decimal marker while in Indian Standards, the current practice is to use a point (.) as the decimal marker.

This standard has been issued in several parts. Other parts in this series are:

Part 1 Vocabulary
Part 2 CMMs used for measuring linear dimensions
Part 3 CMMs with the axis of a rotary table as the fourth axis
Part 5 Coordinate measuring machines (CMMs) using single and multiple stylus contacting probing systems using discrete point and/or scanning measuring mode
Part 6 Estimation of errors in computing Gaussian associated features
Part 7 CMMs equipped with imaging probing systems
Part 8 CMMs with optical distance sensors
Part 9 CMMs with multiple probing systems
Part 12 Articulated arm coordinate measurement machines (CMM)

In this adopted standard, reference appears to certain International Standards for which Indian Standards also exist. The corresponding Indian Standards, which are to be substituted in their respective places, are listed below along with their degree of equivalence for the editions indicated:

International Standard	*Corresponding Indian Standard*	*Degree of Equivalence*
ISO 10360-8 : 2013 Geometrical product specifications (GPS) — Acceptance and reverification tests for coordinate measuring systems (CMS) — Part 8: CMMs with optical distance sensors	IS 15635 (Part 8) : 2019 Geometrical product specifications (GPS) — Acceptance and reverification tests for coordinate measuring systems (CMS): Part 8 CMMs with optical distance sensors	Identical
ISO 10360-9 : 2013 Geometrical product specifications (GPS) — Acceptance and reverification tests for coordinate measuring systems (CMS) — Part 9: CMMs with multiple probing systems	IS 15635 (Part 9) : 2019 Geometrical product specifications (GPS) — Acceptance and reverification tests for coordinate measuring systems (CMS): Part 9 CMMs with multiple probing systems	Identical

In reporting the result of a test or analysis made in accordance with this standard, if the final value, observed or calculated, is to be rounded off, it shall be done in accordance with IS 2 : 2022 'Rules for rounding off numerical values (*second revision*)'.

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Introduction

This document is a geometrical product specification (GPS) standard and is to be regarded as a general GPS standard (see ISO 14638). It influences chain link F of the chain of standards on size, distance, form, orientation, location and run-out.

The ISO/GPS matrix model given in ISO 14638 gives an overview of the ISO/GPS system of which this document is a part. The fundamental rules of ISO/GPS given in ISO 8015 apply to this document and the default decision rules given in ISO 14253-1 apply to specifications made in accordance with this document, unless otherwise indicated.

More detailed information on the relation of this document to other standards and the GPS matrix model can be found in Annex H.

The objective of this document is to provide a well-defined testing procedure for:

a) laser tracker manufacturers to specify performance by maximum permissible errors (MPEs); and

b) to allow testing of these specifications using calibrated and traceable test lengths, test spheres and flats.

The benefits of these tests are that the measured result has a direct traceability to the unit of length, the metre, and that it gives information on how the laser tracker will perform on similar length measurements.

This document is distinct from ISO 10360-2, which is for coordinate measuring machines (CMMs) equipped with contact probing systems, in that the orientation of the calibrated test lengths reflects the different instrument geometry and error sources within the instrument.

Indian Standard

GEOMETRICAL PRODUCT SPECIFICATIONS (GPS) — ACCEPTANCE AND REVERIFICATION TESTS FOR COORDINATE MEASURING SYSTEMS (CMS)

PART 10 LASER TRACKERS

1 Scope

This document specifies the acceptance tests for verifying the performance of a laser tracker by measuring calibrated test lengths, according to the specifications of the manufacturer. It also specifies the reverification tests that enable the user to periodically reverify the performance of the laser tracker. The acceptance and reverification tests given in this document are applicable to laser trackers utilizing a retroreflector, or a retroreflector in combination with a stylus or optical distance sensor, as a probing system. Laser trackers that use interferometric measurement (IFM), absolute distance measurement (ADM) or both can be verified using this document. This document 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.

NOTE Systems which do not track the target, such as laser radar systems, will not be tested for probing performance.

This document does not explicitly apply to measuring systems that do not use a spherical coordinate system. However, interested parties can apply this document to such systems by mutual agreement.

This document specifies:

— performance requirements that can be assigned by the manufacturer or the user of the laser tracker;

— the manner of execution of the acceptance and reverification tests to demonstrate the stated requirements;

— rules for proving comformity;

— applications for which the acceptance and reverification tests can be used.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 10360-8:2013, *Geometrical product specifications (GPS) — Acceptance and reverification tests for coordinate measuring systems (CMS) — Part 8: CMMs with optical distance sensors*

ISO 10360-9:2013, *Geometrical product specifications (GPS) — Acceptance and reverification tests for coordinate measuring systems (CMS) — Part 9: CMMs with multiple probing systems*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

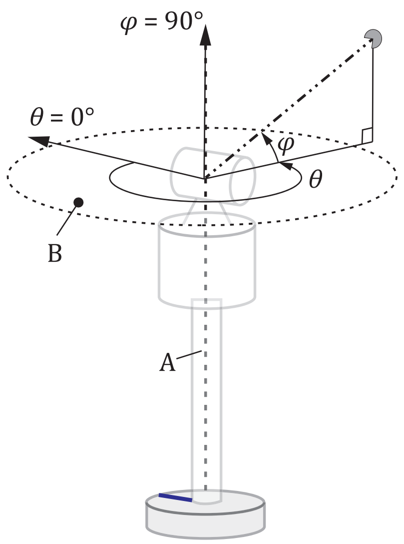
— IEC Electropedia: available at http://www.electropedia.org/

3.1
laser tracker
coordinate measuring system in which a cooperative target is followed with a laser beam and its location determined in terms of a distance (range) and two angles

Note 1 to entry: The two angles are referred to as azimuth, θ, (rotation about a vertical axis – the standing axis of the laser tracker) and either elevation, φ, (angle above a horizontal plane – perpendicular to the standing axis) or zenith (angle from the standing axis).

Note 2 to entry: Care should be used with the symbols associated with spherical coordinate systems, as different conventions exist. For example, the description of a spherical coordinate system in ISO 80000-2 uses the symbols differently and uses the zenith angle (away from vertical) rather than elevation.

Note 3 to entry: See Figure 1



Key

A standing axis

B horizontal plane (of the laser tracker)

θ azimuth angle

φ elevation angle

Figure 1 — Coordinate system of a laser tracker

3.2
interferometric measurement mode
IFM mode
measurement method that uses a laser displacement interferometer integrated in a *laser tracker* (3.1) to determine distance (range) to a target

Note 1 to entry: Displacement interferometers can only determine differences in distance, and therefore require a reference distance (e.g. home position).

3.3
absolute distance measurement mode
ADM mode
measurement method that uses time of flight instrumentation integrated in a *laser tracker* (3.1) to determine the distance (range) to a target

Note 1 to entry: Time of flight instrumentation may include a variety of modulation methods to calculate the distance to the target.

3.4
retroreflector
passive device designed to reflect light back parallel to the incident direction over a range of incident angles

Note 1 to entry: Typical retroreflectors are the cat's-eye, the cube corner and spheres of special material.

Note 2 to entry: Retroreflectors are cooperative targets.

Note 3 to entry: For certain systems, for example laser radar, the retroreflector will possibly be a cooperative target such as a polished sphere.

3.5
spherically mounted retroreflector
SMR
retroreflector (3.4) that is mounted in a spherical housing

Note 1 to entry: In the case of an open-air cube corner, the vertex is typically adjusted to be coincident with the sphere centre.

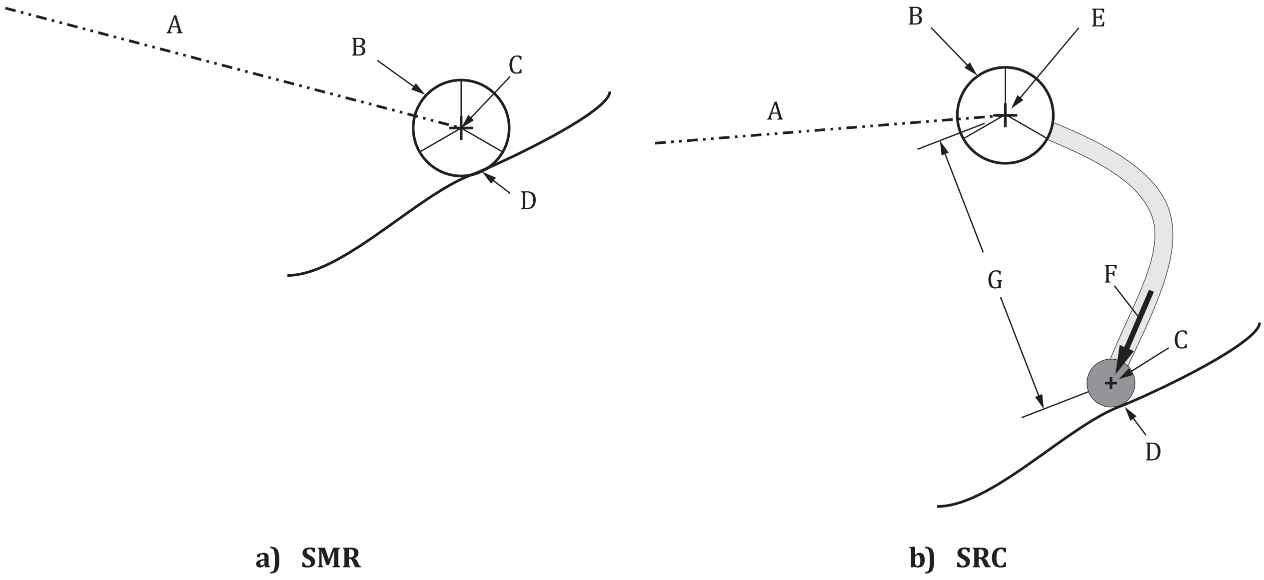
Note 2 to entry: The tests in this document are typically executed with a spherically mounted retroreflector.

Note 3 to entry: See Figure 2.

3.6
stylus and retroreflector combination
SRC
probing system that determines the measurement point utilizing a probe stylus to contact the workpiece, a *retroreflector* (3.4) to determine the base location of the probe, and other means to find the stylus orientation unit vector

Note 1 to entry: The datum for the stylus tip offset (l) is the centre of the retroreflector.

Note 2 to entry: See Figure 2.



Key

A laser beam
B retroreflector
C measurement point
D contact point
E base location
F normal probing direction vector
G stylus tip offset length *l*

Figure 2 — Representation of SMR versus SRC (simplified figures)

3.7
optical distance sensor and retroreflector combination
ODR
probing system that determines the measurement point utilizing an optical distance sensor to measure the workpiece, a *retroreflector* (3.4) to determine the base location of the optical distance sensor and other means to find the orientation of the optical distance sensor

3.8
target nest
nest
device designed to repeatably locate an *SMR* (3.5)

3.9
length measurement error
$E_{Vol:L:LT}$
$E_{Bi:L:LT}$
error of indication when performing an averaged ($E_{Vol:L:LT}$) or bidirectional ($E_{Bi:L:LT}$) point-to-point distance measurement of a calibrated test length using a laser tracker with a stylus tip offset of L

Note 1 to entry: $E_{Vol:0:LT}$ and $E_{Bi:0:LT}$ (used frequently in this document) correspond to the common case of no stylus tip offset, as the retroreflector optical centre is coincident with the physical centre of the probing system for *spherically mounted retroreflectors* (3.5).

3.10
normal CTE material
material with a coefficient of thermal expansion (CTE) between 8×10^{-6}/°C and 13×10^{-6}/°C

Note 1 to entry: Some documents may express CTE in units 1/K or K^{-1}, which is equivalent to 1/°C.

[SOURCE: ISO 10360-2:2009, 3.3, modified — Note 1 to entry added.]

3.11
probing form error
$P_{\text{Form.Sph.1x25:SMR:LT}}$
error of indication within which the range of Gaussian radial distances can be determined by a least-squares fit of 25 points measured by a *laser tracker* (3.1) on a spherical material standard of size

Note 1 to entry: Only one least-squares fit is performed, and each point is evaluated for its distance (radius) from this fitted centre.

3.12
probing size error
$P_{\text{Size.Sph.1x25:SMR:LT}}$
error of indication of the diameter of a spherical material standard of size as determined by a least-squares fit of 25 points measured with a *laser tracker* (3.1)

3.13
location error
two-face error
plunge and reverse error
$L_{\text{Dia.2x1:P\&R:LT}}$
distance, perpendicular to the beam path, between two measurements of a stationary *retroreflector* (3.4), where the second measurement is taken with the *laser tracker* (3.1) azimuth angle at approximately 180° from the first measurement and the laser tracker elevation angle is approximately the same

Note 1 to entry: This combination of axis rotations is known as a 'two-face' or 'plunge and reverse' test.

Note 2 to entry: The laser tracker base is fixed during this test.

3.14
maximum permissible error of length measurement
$E_{\text{Vol:L:LT, MPE}}$
$E_{\text{Bi:L:LT, MPE}}$
extreme value of the *length measurement error* (3.9), $E_{\text{Bi:L:LT}}$ or $E_{\text{Vol:L:LT}}$, permitted by specifications

Note 1 to entry: $E_{\text{Vol:0:LT}}$ and $E_{\text{Bi:0:LT}}$ (used frequently in this document) correspond to the common case of no stylus tip offset, as the retroreflector optical centre is coincident with the physical centre of the probing system for *spherically mounted retroreflectors* (3.5).

3.15
maximum permissible error of probing form
$P_{\text{Form.Sph.1x25:SMR:LT, MPE}}$
extreme value of the *probing form error* (3.11), $P_{\text{Form.Sph.1x25:SMR:LT}}$, permitted by specifications

3.16
maximum permissible error of probing size
$P_{\text{Size.Sph.1x25:SMR:LT, MPE}}$
extreme value of the *probing size error* (3.12), $P_{\text{Size.Sph.1x25:SMR:LT}}$, permitted by specifications

3.17
maximum permissible error of location
$L_{\text{Dia.2x1:P\&R:LT, MPE}}$
extreme value of the location error, $L_{\text{Dia.2x1:P\&R:LT}}$, permitted by specifications

3.18
rated operating condition
operating condition that must be fulfilled, according to specification, during measurement in order that a measuring instrument or measuring system performs as designed

Note 1 to entry: Rated operating conditions generally specify intervals of values for a quantity being measured and for any influence quantity.

Note 2 to entry: Within the ISO 10360 series, the term "as designed" in the definition means "as specified by MPEs".

Note 3 to entry: When the rated operating conditions are not met in a test according to the ISO 10360 series, neither comformity nor non-comformity to specifications can be determined.

[SOURCE: ISO/IEC Guide 99:2007, 4.9, modified — definition revised and Notes 2 and 3 to entry added.]

4 Symbols

For the purpose of this document, the symbols in Table 1 apply.

Table 1 — Symbols of specification quantities

Symbol	Meaning
$E_{\text{Vol:L:LT}}$ $E_{\text{Bi:L:LT}}$	Length measurement error (averaged or bi-directional lengths) where L is the stylus tip offset
$P_{\text{Form.Sph.1x25:SMR:LT}}$	Probing form error
$P_{\text{Size.Sph.1x25:SMR:LT}}$	Probing size error
$L_{\text{Dia.2x1:P\&R:LT}}$	Location error (from two-face tests)
$E_{\text{Vol:L:LT,MPE}}$ $E_{\text{Bi:L:LT,MPE}}$	Maximum permissible error of length measurement where L is the stylus tip offset
$P_{\text{Form.Sph.1x25:SMR:LT,MPE}}$	Maximum permissible error of probing form
$P_{\text{Size.Sph.1x25:SMR:LT,MPE}}$	Maximum permissible error of probing size
$L_{\text{Dia.2x1:P\&R:LT,MPE}}$	Maximum permissible error of location (from two-face tests)
Accessory sensor testing – SRC	
$P_{\text{Form.Sph.1x25:SRC:LT}}$	Probing form error for SRC
$P_{\text{Size.Sph.1x25:SRC:LT}}$	Probing size error for SRC
$P_{\text{Dia.15x1:SRC:LT}}$	Orientation error for SRC
$P_{\text{Form.Sph.1x25:SRC:LT,MPE}}$	Maximum permissible error of probing form for SRC
$P_{\text{Size.Sph.1x25:SRC:LT,MPE}}$	Maximum permissible error of probing size for SRC
$P_{\text{Dia.15x1:SRC:LT,MPE}}$	Maximum permissible error of orientation for SRC
Accessory sensor testing – ODR	
$P_{\text{Form.Sph.1 × 25:ODR:LT}}$	Probing form error for ODR (25 points)
$P_{\text{Form.Sph.D95 \%:ODR:LT}}$	Probing form error for ODR (95 % of the points)
$P_{\text{Size.Sph.1 × 25:ODR:LT}}$	Probing size error for ODR (25 points)
$P_{\text{Size.Sph.All:ODR:LT}}$	Probing size error for ODR (all points)
$E_{\text{Form.Pla.D95 \%:ODR:LT}}$	Flat form error of measurement with ODR (95 % of the points)
$P_{\text{Form.Sph.1 × 25:ODR:LT,MPE}}$	Maximum permissible error of probing form for ODR (25 points)
$P_{\text{Form.Sph.D95 \%:ODR:LT,MPE}}$	Maximum permissible error of probing form for ODR (95 % of the points)
$P_{\text{Size.Sph.1 × 25:ODR:LT,MPE}}$	Maximum permissible error of probing size for ODR (25 points)
$P_{\text{Size.Sph.All:ODR:LT,MPE}}$	Maximum permissible error of probing size for ODR (all points)

Table 1 *(continued)*

Symbol	Meaning
$E_{\text{Form.Pla.D95 \%:ODR:LT,MPE}}$	Maximum permissible error of flat form measurement with ODR (95 % of the points)
Multiple sensor testing	
$P_{\text{Form.Sph.}n\text{x25::MPS.LT}}$	Multiple probing system form error
$P_{\text{Size.Sph.}n\text{x25::MPS.LT}}$	Multiple probing system size error
$L_{\text{Dia.}n \times \text{25::MPS.LT}}$	Multiple probing system location error
$P_{\text{Form.Sph.}n\text{x25::MPS.LT,MPE}}$	Maximum permissible multiple probing system form error
$P_{\text{Size.Sph.}n\text{x25::MPS.LT,MPE}}$	Maximum permissible multiple probing system size error
$L_{\text{Dia.}n \times \text{25::MPS.LT,MPE}}$	Maximum permissible multiple probing system location error

NOTE 1 For the common case of length testing with an SMR, L will be equal to 0 (e.g. $E_{\text{Bi:0:LT}}$).

NOTE 2 The specific combinations of sensors for the multiple probing system errors depend on the sensors provided with the laser tracker system. It is possible to explicitly capture the combination in the symbol, such as $P_{\text{Size.Sph.2x25:ODS,SMR:MPS.LT}}$, where the symbols indicating sensors are listed alphabetically.

NOTE 3 In the multiple sensor testing entries, n (in $n \times 25$) is the number of sensors being involved ($n \geq 2$).

5 Rated operating conditions

5.1 Environmental conditions

Limits for permissible environmental conditions such as temperature conditions, air pressure, humidity and vibration at the site of usage or testing that influence the measurements shall be specified by:

— the manufacturer, in the case of acceptance tests;

— the user, in the case of reverification tests.

In both cases, the user is free to choose the environmental conditions under which the testing will be performed within the specified limits (Form 1 in Annex A is the recommended method for specifying these conditions).

If the user wishes to have testing performed under environmental conditions other than the ambient conditions of the test site (e.g. at an elevated or lowered temperature), agreement between parties regarding who bears the cost of environmental conditioning should be attained.

5.2 Operating conditions

The conditions required by the manufacturer in order to meet the MPE specification shall be specified (e.g. as given in a specification sheet).

In addition, the laser tracker shall be operated using the procedures given in the manufacturer's operating manual when conducting the tests given in Clause 6. Specific areas in the manufacturer's manual to be adhered to include:

a) machine start-up/warm-up cycles;

b) machine compensation procedures;

c) cleaning procedures for retroreflector and nests;

d) SMR or SRC qualification;

e) location, type and number of environmental sensors (i.e. “the weather station”);

f) location, type and number of thermal workpiece sensors;

g) stability and vibration isolation of the mounting.

6 Acceptance tests and reverification tests

6.1 General

In the following:

— acceptance tests are executed according to the manufacturer's specifications and procedures that are in conformity with this document;

— reverification tests are executed according to the user's specifications and the manufacturer's procedures.

If specifications permit, the laser tracker may be tested in an orientation other than the normal upright, vertical orientation. In every case, the azimuth and elevation angles will be oriented with respect to the laser tracker. The position and orientation of the calibrated test lengths with respect to the laser tracker shall be clearly defined before the tests begin. In general, the calibrated test lengths will not rotate with the laser tracker. However, the locations for probing and two-face tests will maintain a fixed relationship with respect to the laser tracker's standing axis (i.e. they will rotate with the laser tracker). For example, if the laser tracker is mounted with its standing axis horizontal, the 'above' and 'below' directions described in Table 2 and Table 3 will be parallel to the standing axis.

Where least squares (Gaussian) fitting is used in the derivation of test results, this shall be an unconstrained fit to the data, unless constraints to the fitting are explicitly stated.

As the two-face tests can be performed quickly and will immediately reveal problems with the laser tracker geometry and its correction, it is recommended that some or all of these tests be performed first.

6.2 Probing size and form errors

6.2.1 Principle

The principle of this test procedure is to measure the size and form of a test sphere using 25 points probed with the SMR, SRC or ODR. Refer to Annex F or Annex G for additional information about testing with the SRC or ODR sensors, respectively. A least-squares sphere fit of the 25 points is examined for the errors of indication for form and size. This analysis yields the form error, $P_{\text{Form.Sph.1x25:SMR:LT}}$, and the size error, $P_{\text{Size.Sph.1x25:SMR:LT}}$.

NOTE 1 Probing errors $P_{\text{Form.Sph.1x25:SMR:LT}}$ and $P_{\text{Size.Sph.1x25:SMR:LT}}$ do not apply to laser radar systems.

NOTE 2 These are tests of the laser tracker system's ability to locate individual points in space. These tests are not intended to check any of the specifications supplied by an SMR manufacturer, although errors in the SMR will influence the test results.

NOTE 3 When performing this test with an SMR, three types of errors in the SMR can influence the results of this test. If the sphere within which the retroreflector is mounted is not a perfect sphere, this will influence the test result. Also, if the mirrored surfaces which comprise the retroreflector are not mutually orthogonal, or if their point of intersection is not coincident with the sphere centre, the test result will be affected.

6.2.2 Reference artefact

The material standard of size, i.e. the test sphere, shall have a nominal diameter not less than 10 mm and not greater than 51 mm. The test sphere shall be calibrated for size and form.

NOTE It can be difficult to make measurements on smaller test spheres due to interference with the sphere mount.

6.2.3 Procedure

Mount the test sphere so that a full hemisphere can be probed. When an SMR is used for probing, the test sphere support should be oriented away from the laser tracker. For an SRC, the support should be located away from the normal probing direction (see Figure 2).

The test sphere should be mounted rigidly to minimize errors due to bending.

Measure and record 25 points. The points shall be approximately evenly distributed over at least a hemisphere of the test sphere. Their position shall be at the discretion of the user and, if not specified, the following probing pattern is recommended (see Figure 3):

— one point on the pole of the test sphere;

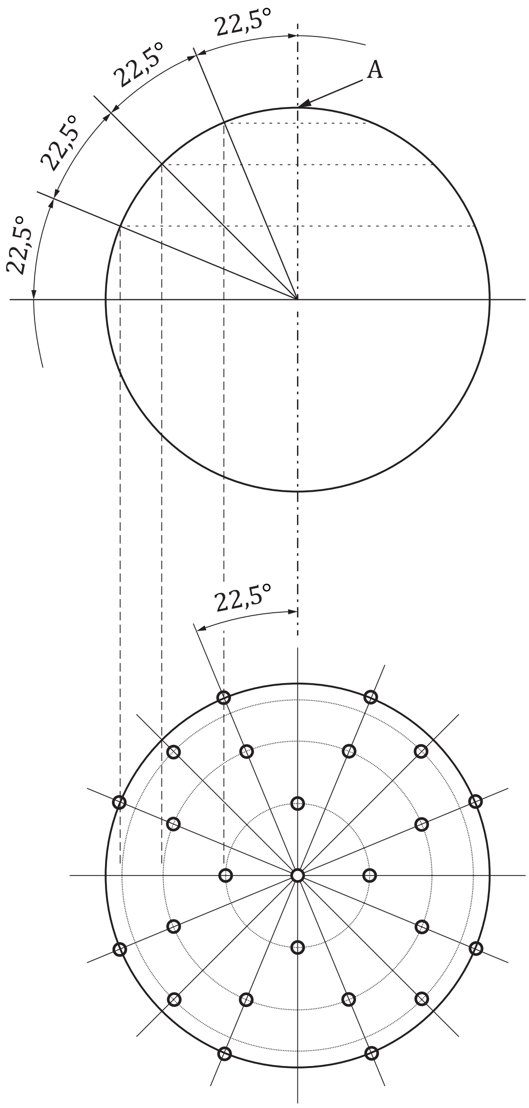
— four points (equally spaced) 22,5° below the pole;

— eight points (equally spaced) 45° below the pole and rotated 22,5° relative to the previous group;

— four points (equally spaced) 67,5° below the pole and rotated 22,5° relative to the previous group;

— eight points (equally spaced) 90° below the pole (i.e. on the equator) and rotated 22,5° relative to the previous group.

NOTE Due to the manual nature of point measurement with laser trackers, it is recognized that the exact points recommended will possibly not be measured.



Key

A pole

Figure 3 — Location of probing points

The results of these tests can be highly dependent on the distance of the retroreflector from the laser tracker, especially for the SRC and ODR sensors. Therefore, the test shall be performed at the required distances from the laser tracker, as indicated in Table 2.

Table 2 — Probe testing locations

Distance from laser tracker	Required for these sensors	Height relative to laser tracker centre of rotation[b]
< 2 m[a]	SMR, SRC, ODR	approximately same height
approximately 10 m	SRC, ODR	more than 1 m above or below

[a] Where a manufacturer's specifications explicitly state that an SRC or ODR sensor only performs at a distance greater than 2 m from the laser tracker, the test shall be performed at the minimum stated distance.

[b] The probe testing locations will have the same location and orientation relative to the laser tracker's standing axis if the laser tracker is not oriented vertically.

6.2.4 Derivation of test results

6.2.4.1 Size errors

Using all 25 measurements, compute the Gaussian associated sphere. Record the diameter of this sphere. The signed difference of this (measured) diameter from the calibrated (reference) diameter of the test sphere, i.e. $D_{MEAS} - D_{REF}$, is the probing size error, $P_{Size.Sph.1x25:xxx:LT}$ (where xxx is replaced by SMR, SRC or ODR, as applicable).

6.2.4.2 Form errors

For each of the 25 measurements, calculate the Gaussian radial distance, *R,* as the distance from the centre of the least-squares sphere to the measurement point. Record the range of these values, i.e. $R_{max} - R_{min}$, as the probing form error, $P_{Form.Sph.1x25:xxx:LT}$ (where xxx is replaced by SMR, SRC or ODR, as applicable).

6.3 Location errors (two-face tests)

6.3.1 Principle

The principle of this test procedure is to detect geometrical errors of the laser tracker by measuring the location of a stationary retroreflector twice in different laser tracker configurations. These configurations are obtained by 1) measuring in normal mode, 2) with the azimuth angle at approximately 180° from the first configuration and moving the elevation angle until pointing at the retroreflector, and then 3) allowing both azimuth and elevation angles to change (slightly) to reacquire the retroreflector. The apparent distance, perpendicular to the laser beam, between the two measurements of the retroreflector yields the test result, $L_{Dia.2x1:P\&R:LT}$.

6.3.2 Reference artefact

The equipment for this test is a target nest that is mounted rigidly at the positions required in Table 3.

6.3.3 Procedure

Mount the target nest so that the nest and its support will not interfere with measurement of the retroreflector. The target nest should be mounted rigidly to minimize uncertainty in the measurements.

Place the SMR in the nest and measure the location of the SMR using the two angles and the distance (range). Rotate both angular axes of the laser tracker by the appropriate angles and reacquire the retroreflector. Measure this location of the retroreflector in the angles only, using the distance value from the first measurement.

The results of these tests can be highly dependent on the distance of the SMR from the laser tracker and influenced by the laser tracker's angular orientation. Therefore, these tests shall be performed at two or more distances from the laser tracker and at three different orientations, as indicated in Table 3. The distance from the laser tracker is the horizontal distance between the laser tracker and the retroreflector position, and the orientation angle is the nominal azimuth angle of the laser tracker when it is pointing at the retroreflector.

The two-face test results for repeated measurements at the same SMR nest location may be used to evaluate the repeatability of the measuring system.

Table 3 — Two-face measurement positions

Two-face test positions	Retroreflector at least 1 m above height of the laser tracker centre of rotation	Retroreflector at height of the laser tracker centre of rotation	Retroreflector at least 1 m below height of the laser tracker centre of rotation
1,5 m from laser tracker[a]	Positions 1 to 3 Any 3 azimuth angles, separated by 120°	Positions 4 to 6 Any 3 azimuth angles, separated by 120°	Positions 7 to 9 Any 3 azimuth angles, separated by 120°
6 m from laser tracker[a]	Positions 10 to 12 Any 3 azimuth angles, separated by 120°	Positions 13 to 15 Any 3 azimuth angles, separated by 120°	Positions 16 to 18 Any 3 azimuth angles, separated by 120°
User-selectable distance from laser tracker	Position 19	Position 20	Position 21

[a] The distance from laser tracker should be within 10 % of the nominal distance, and azimuth angle within 5°.

NOTE The testing locations will have the same location and orientation relative to the laser tracker's standing axis if the laser tracker is not oriented vertically.

6.3.4 Derivation of test results

Calculate the location error for these two measured locations. This distance between the two locations is the location error, $L_{\text{Dia.2x1:P\&R:LT}}$.

If the two measured locations correspond to (θ_1, φ_1, R_1) and (θ_2, φ_2, R_2) in spherical coordinates, the calculated location error for these two locations is calculated according to Formula (1).

$$L_{\text{Dia.2x1:P\&R:LT}} = R_1 \sqrt{(\varphi_1 - \varphi_2)^2 + [(|\theta_1 - \theta_2| - \pi)\cos\varphi_1]^2} \quad (1)$$

where

φ_1 is the elevation angle of the first location in radians;

φ_2 is the elevation angle of the second location in radians;

θ_1 is the azimuth angle of the first location in radians;

θ_2 is the azimuth angle of the second location in radians;

R_1 is the distance value of the first location.

φ_1 and φ_2 are approximately equal, and θ_1 and θ_2 are approximately π radians (180°) apart. Only the first distance value, R_1, is used in the calculation of the location error, as this test is not intended to capture differences in the distance values. Instruments using ADM mode will report the second distance, R_2, while instruments using IFM mode will not.

NOTE 1 For this document, the elevation angle φ is zero at the horizontal.

NOTE 2 Although φ_1 and φ_2 are approximately equal, it is possible that the instrument will report them as significantly different values (0,1 rad, and π – 0,1 rad) as they occur at different locations on the laser tracker's encoder.

NOTE 3 The subscript "Dia" in the symbol $L_{\text{Dia.2x1.P\&R.:LT}}$ refers to the diameter of the minimum circumscribing sphere containing the two reported locations. For two locations, this diameter is the distance between the locations.

NOTE 4 The value given in Formula (1) is an approximation to the actual distance between the locations, but the difference is negligible in this application.

6.4 Length errors

6.4.1 General

The tests of length measurement errors comprise 41 length measurements, described in Table 4. Of these lengths, the user is free to choose six of the calibrated test length positions.

One or more formulas shall be specified by the manufacturer so that the MPE can be uniquely determined for any point-to-point measurement in the measuring volume. If more than one formula is specified, a rule shall be unambiguously stated so that it is always clear which formula is to be used. The form of the formulas is the choice of manufacturer. All manufacturers shall have a means of specifying the MPEs for the prescribed calibrated test lengths measured in the positions described in Table 4.

NOTE See Annex D for additional information regarding MPE formulas.

For the purposes of comparing the specifications of different instruments, the MPEs for positions 1 to 29 and 41 shall be explicitly stated in a table such as shown in Figure A.1 at the standoff distances indicated in Table 4 and a test length of 2,75 m. Where the standoff distance is as close as practical, a distance of 0,5 m shall be used in computing the MPE.

For the purposes of testing, the calibrated test lengths may be within the ranges of length (i.e. 2,25 m to 2,75 m) stated in Table 4, and the MPEs used to determine comformity of the laser tracker will be recalculated based on the actual length of the test length used in the test. MPEs for user-defined lengths will be calculated at the time of testing.

6.4.2 Principle

The length measurement errors describe the three-dimensional deviation behaviour of the laser tracker in the specified measuring volume. This deviation behaviour is caused by the superposition of different individual deviations, such as uncorrected systematic deviations of the length-measuring system and the angle encoders, random measuring deviations and geometrical imperfections in the rotary axes and/or of the probing system. As the deviation behaviour depends, among other things, on the mode of operation, different values of the characteristics may result in different modes of operation (interferometric or absolute distance measurement, vertical or horizontal installation of the laser tracker and the use of an SMR, SRC or ODR). If a specific mode of operation is not indicated in the manufacturer's specification, this specification shall apply to all modes of operation available to the user. It is recommended, if multiple sensors are available, that the length tests are performed with the SMR to determine length measurement errors. The performance of the other sensors shall then be determined by following the procedures in Annex F and Annex G.

NOTE Lines f and g of the specification sheet (Annex A) are examples of where modes of operation will possibly be specified by the manufacturer.

In most cases, length testing is performed with an SMR only. Additional tests for accessory probing systems are given in Annex F and Annex G. If both IFM mode and ADM mode are specified, perform a subset of two complete tests according to 6.4.4.2.

6.4.3 Reference artefacts

A calibrated test length may be realized in a number of ways, including scale bars, target nests mounted on walls or freestanding structures, use of a rail-and-carriage system, gauge blocks and ball bars. Calibrated test lengths shall be in accordance with Annex B. The test length should be appropriate for the specifications being tested (e.g. E_{Vol} or E_{Bi}).

A laser tracker uses one linear axis and two rotary axes to determine the location of a retroreflector. The normative locations in Table 4 include tests that span at least 66 % of the manufacturer-specified measuring ranges of the linear and the two angular axes, respectively. Positions 1 and 2 accomplish this for each rotary axis separately, while positions 36 to 40 accomplish this for the ranging (linear) axis. The angular range of a measurement is determined by both the test length to be measured and its distance from the laser tracker. It is therefore possible to obtain a variety of angular measurements using a single calibrated test length. For this reason, the test lengths in positions 1 to 29 of Table 4 shall be between 2,25 m and 2,75 m.

The manufacturer shall state the upper, and optionally lower, limits of the CTE of the calibrated test length. The manufacturer may calibrate the CTE of a calibrated test length. The manufacturer shall specify the maximum permitted (k = 2) uncertainty of the CTE of the calibrated test length. In cases where the calibrated test length is composed of an averaged length and other information as described in Annex B, the CTE shall be considered to be that of the averaged length. The default for a calibrated test length is a normal CTE material unless the manufacturer's specifications explicitly state otherwise.

A reference laser interferometer may be used to establish calibrated test lengths. A laser interferometer that is corrected for the index of refraction of air has a zero CTE ($\alpha = 0$). Hence, if it is used to produce a calibrated test length, this test length is considered a low CTE material. Additionally, if the reference laser has a workpiece (material) temperature sensor, then the workpiece CTE in the laser's software shall be set to 0. If a temperature-compensated laser tracker is being tested, the workpiece CTE in the laser tracker software shall be set to 0 when measuring these test lengths.

If the calibrated test length is not a normal CTE material, then the corresponding $E_{\mathrm{Vol:0:LT,MPE}}$ or $E_{\mathrm{Bi:0:LT,MPE}}$ values are designated with an asterisk (*) and an explanatory note shall be provided describing the CTE of the calibrated test length.

EXAMPLE $E_{\mathrm{Vol:0:LT,MPE}}{}^{*}$ or $E_{\mathrm{Bi:0:LT,\,MPE}}{}^{*}$

* Calibrated test length is carbon fibre with a CTE no greater than $0{,}5 \times 10^{-6}$/°C and with an expanded uncertainty (k = 2) U(CTE) no greater than $0{,}3 \times 10^{-6}$/°C.

For cases where the length tests are performed using calibrated test lengths having a CTE less than 2×10^{-6}/°C (thus being a non-normal CTE), an additional “synthetic length test” shall be performed, as described in Annex C.

NOTE 1 Due to the large size of test lengths required for testing laser trackers, it is common for this low CTE option to occur in the laser tracker testing.

NOTE 2 Because of the difficulty in establishing long test lengths, especially in real environments, the test value uncertainty will possibly be dominated by the uncertainty of calibration of test lengths.

6.4.4 Procedure

6.4.4.1 Required test length positions

Place the calibrated test length(s) at each location and orientation relative to the laser tracker described in Table 4 and shown in Figure 4. If, in the case of IFM mode measurements, a beam break occurs during a length measurement, the measurement during which the beam was broken must be restarted. In the case of ADM mode measurements, the beam shall be broken before each reflector measurement (at either end of each length measurement), forcing the laser tracker to re-establish the distance to the reflector as part of the ADM mode measurement process. Each entry in Table 4 shall have a manufacturer-specified MPE that is applicable to that particular calibrated test length in the orientation and location specified.

In Table 4, the laser tracker origin is at the intersection of the two rotary axes, and the azimuth angle has clockwise sense about the vertical standing axis of the laser tracker, with 0° azimuth set by the non-rotating laser tracker base. The distance of the calibrated test length from the laser tracker origin is shown by distance d in Figure 4.

NOTE In many instances, it can be easier to move or reorient the laser tracker than to move the test length.

Table 4 — Measurement positions

Position number (basic positions)	Distance from laser tracker origin	Description of test length position (shown in Figure 4)	Azimuth angle(s)
1	As close as practical	Horizontal, centred (i.e. the ends of the test length are equidistant from the laser tracker) and at laser tracker height[a]	at any azimuth
2	As close as practical	Vertical, centre of the length at laser tracker height (ends of the test length equidistant from the laser tracker)[b]	at any azimuth
3 to 6	3 m	Horizontal, centred (i.e. the ends of the test length are equidistant from the laser tracker) and at laser tracker height	any 4 azimuths, separated by 90°
7	3 m	Vertical, centre of the length at laser tracker height (ends of the test length equidistant from the laser tracker)	at any azimuth
8 to 11	3 m	Right diagonal, centred (i.e. the ends of the test length are equidistant from the laser tracker) and the centre of the length is at laser tracker height	any 4 azimuths, separated by 90°
12 to 15	3 m	Left diagonal, centred (i.e. the ends of the test length are equidistant from the laser tracker) and the centre of the length is at laser tracker height	any 4 azimuths, separated by 90°
16 to 19	6 m	Horizontal, centred (i.e. the ends of the test length are equidistant from the laser tracker) and at laser tracker height	any 4 azimuths, separated by 90°
20 to 23	As close as practical	Horizontal, not centred (i.e. the laser tracker is directly in front of one end of the test length) and at laser tracker height	any 4 azimuths, separated by 90°
24	As close as practical	Vertical, not centred (i.e. the laser tracker is directly in front of one end of the length)	at any azimuth
25 to 28	As close as practical	Diagonal, not centred (i.e. the laser tracker is directly in front of the intersection of the horizontal and vertical lines through either end of the test length)	any 4 azimuths, separated by 90°
29	As close as practical	Horizontal, centred directly above (as much as that is possible) the laser tracker itself	at any azimuth
30 to 35	User-selectable[c]	Chosen by the user to reflect common measuring conditions	at any azimuth
36 to 40	Five ranging test distances	These tests cover 66 % of the linear axis (IFM mode or ADM mode) of the laser tracker[d,e]	at any azimuth
41	Synthetic length test	Follow the requirements of Annex C (only required for low-CTE calibrated test length case)	at any azimuth

[a] This test covers 66 % of the horizontal angle measurement range of the laser tracker, if the maximum angle is considered to be 180° for a single point-to-point measurement.

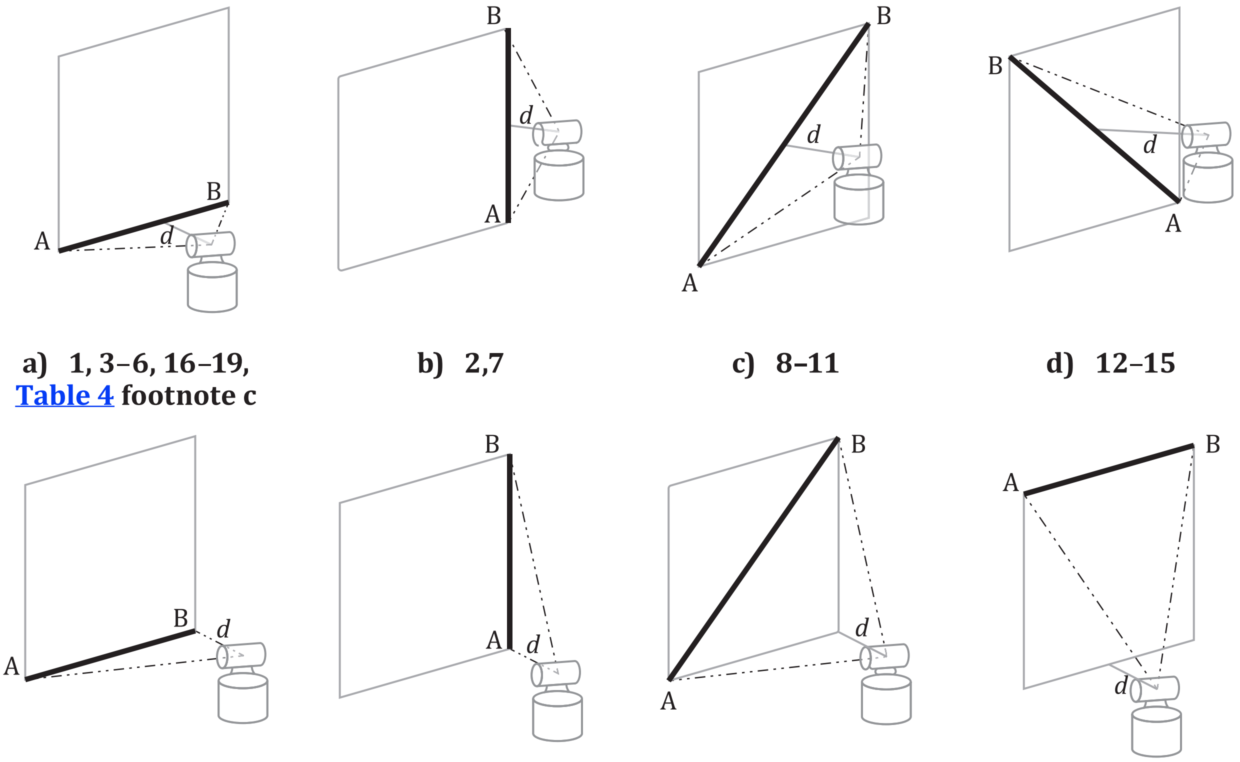
[b] This test covers 66 % of the vertical angle measurement axis of the laser tracker.

[c] One particular test for horizontal encoder errors is a series of longer test lengths measured at a longer distance from the laser tracker. For this test it is recommended that a length of 7 m to 9 m at a distance of 7 m to 9 m is measured, at azimuth angles of 0°, 30°, 60°, 90°, 120° and 150°.

[d] The distance between the two measured points used to evaluate the longest test length shall be at least 66 % of the manufacturer-specified maximum measurement range of the laser tracker, unless there is mutual agreement otherwise between manufacturer and the user.

[e] For users who do not intend to use the full measurement range of the laser tracker, the user may choose lengths 36 to 40 that span a shorter range than 66 % of the maximum specified range and shall note the new maximum range on the test report. This does not influence any of the other specifications in this document.

In the ranging tests (lengths 36 to 40), each of the five calibrated test lengths is defined as a two-point distance in line with the laser tracker (i.e. with end points having approximately the same azimuth and elevation angles as shown in Figure D.2). However, it is permitted to measure a first point close to the laser tracker (e.g. less than 1,5 m from the laser tracker) and then the five successive points at increasing distances, where the five test lengths are all calculated from the common first point. In explanation, if the points are labelled A (closest) to F (farthest), a sequence of measurements such as (AB, AC, AD, AE, AF) are the specified test lengths to which the MPE applies. However, a measurement sequence such as (A, B, C, D, E, F) is permitted to evaluate the ranging capability of the laser tracker, because the repeatability of remeasuring nest A is expected to be small compared to the errors observed in the long lengths measured in the ranging tests. The user may, however, require that the full formal test procedure be conducted at each test length; this remeasures the A location five times as in (AB, AC, AD, AE, AF) or (AB, CA, AD, EA, AF). The distribution of the test lengths shall be approximately evenly spaced, with the longest length (AF) spanning at least 66 % of the manufacturer-specified maximum measuring range of the instrument.



a) 1, 3–6, 16–19, Table 4 footnote c **b) 2,7** **c) 8–11** **d) 12–15**

e) 20–23 **f) 24** **g) 25–28** **h) 29**

Key

A and B ends of the test length

d Shortest distance from the laser tracker origin to a vertical plane containing the test length. Where the test length is vertical (e.g. cases b and f), the plane is also perpendicular to a horizontal line from the laser tracker origin to a line containing the test length.

Figure 4 — Positions for test lengths (positions 1 to 29)

In some cases, calibrated test lengths that are sufficiently long to span 66 % of the instrument's measuring range may not be available. In these cases, both parties may agree to use other means to generate a calibrated test length. These can include length standards that are “stitched” together (i.e. overlapped end-to-end) to form a longer calibrated test length, or laser-based calibrated test lengths, such as those consisting of a line of nests whose nest-to-nest distances are calibrated with a reference interferometer or using multilateration. In such cases, the procedure shall be documented and the uncertainties associated with these techniques shall be considered carefully, as they contribute to the test value uncertainty.

The tester should use extreme care to be certain that the environment and the test length end points are stable for the measurement of calibrated test lengths 36 to 40. It is common that these lengths are established using a reference interferometer in air, and variability in the environment and in the nest locations can contribute to uncertainty in the calibrated test length, which contributes to the test value uncertainty of the length measurement error value.

6.4.4.2 Testing of laser trackers with both IFM mode and ADM mode specified

A laser tracker may have both IFM mode and ADM mode specified by the manufacturer. It is common that the major difference in the specifications for these two modes is in the MPEs of the ranging lengths (lengths 36 to 40 from Table 4). In cases where the MPEs are the same for the two modes, it is permissible to test all of the lengths in ADM mode, with the exception of lengths 1, 2 and 36 to 40 in Table 4, which shall be tested in both modes.

If the MPEs given by the specifications for IFM mode measurements are smaller in absolute value than those of the ADM mode measurements, it is also permissible to test in ADM mode only, with the exception of those test lengths noted above (1, 2 and 36 to 40).

6.4.5 Derivation of test results

For each of the length measurements, determine the length measurement error, $E_{\mathrm{Vol:0:LT}}$ or $E_{\mathrm{Bi:0:LT}}$, by obtaining the difference between the indicated value and the calibrated value of each test length. The indicated value of a particular measurement of a calibrated test length may be corrected by the laser tracker to account for systematic errors, or thermally induced errors (including thermal expansion) if the laser tracker has accessory devices for this purpose. Manual correction of the results obtained from the computer output to account for temperature or other corrections shall not be allowed when the environmental conditions satisfy the conditions of 5.1.

For each length measured, calculate a corresponding MPE value ($E_{\mathrm{Vol:0:LT,\ MPE}}$ or $E_{\mathrm{Bi:0:LT,\ MPE}}$ value) based on the manufacturer's MPE specification.

NOTE The manufacturer's MPE specification will, in general, be a formula.

7 Conformity with specification

7.1 Acceptance tests

The probing performance of the laser tracker is verified if:

— none of the probing form errors, $P_{\mathrm{Form.Sph.1x25:SMR:LT}}$, is greater than the relevant maximum permissible probing form error, $P_{\mathrm{Form.Sph.1x25:SMR:LT,\ MPE}}$, as specified by the manufacturer and taking into account the test value uncertainty,

and

— none of the absolute values of the probing size errors, $P_{\mathrm{Size.Sph.1x25:SMR:LT}}$, is greater than the relevant maximum permissible probing size error, $P_{\mathrm{Size.Sph.1x25:SMR:LT,\ MPE}}$, as specified by the manufacturer and taking into account the test value uncertainty.

Report the measured probing form error and the measured probing size error (with its respective sign). If any of the probing tests fails, repeat the measurement at that position three times, attempting to replicate the 25 measurement points used in the failed test. All three of these repeated probing tests are required to be successful. The largest (absolute value) error of the three is reported for that test (with respective sign in the case of the probing size test.

The two-face (location error) performance of the laser tracker is verified if none of the location errors, $L_{\mathrm{Dia.2x1:P\&R:LT}}$, is greater than the relevant maximum permissible location error, $L_{\mathrm{Dia.2x1:P\&R:LT,\ MPE}}$, as specified by the manufacturer and taking into account the test value uncertainty.

Report the location errors obtained. If one of the two-face tests fails, repeat the measurement at that position three times. The largest (absolute value) error of the three is reported for that test.

The length-measuring performance of the laser tracker is verified if the length measurement errors (values of $E_{Vol:0:LT}$ or $E_{Bi:0:LT}$), are within the MPE of length measurement, $E_{Vol:0:LT, MPE}$ or $E_{Bi:0:LT, MPE}$, as specified by the manufacturer, taking into account the test value uncertainty.

Report the length measurement errors. No more than two of the length measurement errors can be outside of specification. Any length measuring outside of specification shall be remeasured three times, and each of these measurements is required to be within the specification. The largest (absolute value) error of each set of three measurements is reported for that test.

7.2 Reverification tests

Reverification tests are performed as in 7.1, but specifications are made by the user (following the manufacturer's procedures).

8 Applications

8.1 Acceptance test

In a contractual situation between a manufacturer and a user such as that described in a purchasing contract, maintenance contract, repair contract, renovation contract or upgrading contract, the acceptance test specified in this document may be used as a test for verifying the performance of the laser tracker used for measuring linear dimensions in accordance with the specification for the stated MPEs, $E_{Vol:0:LT,MPE}$ or $E_{Bi:0:LT,MPE}$, $P_{Form.Sph.1x25:SMR:LT,MPE}$, $P_{Size.Sph.1x25:SMR:LT,MPE}$ and $L_{Dia.2x1:P\&R:LT,MPE}$, as agreed upon by the manufacturer and the user.

The manufacturer is permitted to specify detailed limitations applicable for $E_{Vol:0:LT,MPE}$ or $E_{Bi:0:LT,MPE}$, $P_{Form.Sph.1x25:SMR:LT,MPE}$, $P_{Size.Sph.1x25:SMR:LT,MPE}$ and $L_{Dia.2x1:P\&R:LT,MPE}$. If no such specification is given, $E_{Vol:0:LT,MPE}$ or $E_{Bi:0:LT,MPE}$, $P_{Form.Sph.1x25:SMR:LT,MPE}$, $P_{Size.Sph.1x25:SMR:LT,MPE}$ and $L_{Dia.2x1:P\&R:LT,MPE}$ apply for any location and orientation of the calibrated test length in the measuring volume of the laser tracker.

A graphical presentation of the test results compared with the appropriate MPE values can be helpful.

8.2 Reverification test

In an organization's internal quality assurance system, the performance verification described in this document can be used as a reverification test to verify the performance of the laser tracker used for measuring linear dimensions in accordance with the specification for the MPEs, $E_{Vol:0:LT,MPE}$ or $E_{Bi:0:LT,MPE}$, $P_{Form.Sph.1x25:SMR:LT,MPE}$, $P_{Size.Sph.1x25:SMR:LT,MPE}$ and $L_{Dia.2x1:P\&R:LT,MPE}$, as stated by the user. The user is permitted to state the values of, and to specify detailed limitation applicable to, $E_{Vol:0:LT,MPE}$ or $E_{Bi:0:LT,MPE}$, $P_{Form.Sph.1x25:SMR:LT,MPE}$, $P_{Size.Sph.1x25:SMR:LT,MPE}$ and $L_{Dia.2x1:P\&R:LT,MPE}$.

It is recommended that no fewer than the 41 calibrated test lengths from Table 4 be used. The lengths in Table 4 are a minimal set chosen to reveal the geometrical errors of the laser tracker[11].

NOTE 1 The tester accounts for the test value uncertainty according to ISO 14253-1; accordingly, a reverification test (where typically the tester is the user) can have a different acceptance zone than in an acceptance test.

NOTE 2 In acceptance testing, the acceptance zone is obtained from the manufacturer’s specifications. In reverification testing, the reverification limits can be derived from the user’s metrological needs.

A graphical presentation of the test results compared with the appropriate MPE values can be helpful.

8.3 Interim check

In an organization's internal quality assurance system, a reduced performance verification may be used periodically to provide confidence through sample measurements that the laser tracker conforms with specified requirements regarding the MPEs, $E_{Vol:0:LT,MPE}$ or $E_{Bi:0:LT,MPE}$, $P_{Form.Sph.1x25:SMR:LT,MPE}$, $P_{Size.Sph.1x25:SMR:LT,MPE}$ and $L_{Dia.2x1:P\&R:LT,MPE}$.

The extent of the interim testing may be modified by using fewer measurements and different test length positions; a possible implementation strategy is described in Annex E.

A graphical presentation of the test results compared with the appropriate MPE values can be helpful.

9 Alternative unformatted presentation of symbols

The symbols in Clause 4 are not suitable for all uses (e.g. in product documentation, in drawings or in data sheets). Table 5 gives the alternative, unformatted presentations that are also allowed.

Table 5 — Symbols and corresponding indications in product documentation, drawings and data sheets

Symbol used in this document	Corresponding indication
$E_{\mathrm{Vol}:l:\mathrm{LT}}$ $E_{\mathrm{Bi}:l:\mathrm{LT}}$	`E[Vol:l:LT]` `E[Bi:l:LT]`
$P_{\mathrm{Form.Sph.1x25:SMR:LT}}$	`P[Form.Sph.1x25:SMR:LT]`
$P_{\mathrm{Form.Sph.1x25:SRC:LT}}$	`P[Form.Sph.1x25:SRC:LT]`
$P_{\mathrm{Form.Sph.1x25:ODR:LT}}$	`P[Form.Sph.1x25:ODR:LT]`
$P_{\mathrm{Size.Sph.1x25:SMR:LT}}$	`P[Size.Sph.1x25:SMR:LT]`
$P_{\mathrm{Size.Sph.1x25:SRC:LT}}$	`P[Size.Sph.1x25:SRC:LT]`
$P_{\mathrm{Size.Sph.1x25:ODR:LT}}$	`P[Size.Sph.1x25:ODR:LT]`
$L_{\mathrm{Dia.2x1:P\&R:LT}}$	`L[Dia.2x1:P&R:LT]`
$P_{\mathrm{Dia.15x1:SRC:LT}}$	`P[Dia.15x1:SRC:LT]`
$P_{\mathrm{Form.Sph.1x25:SRC:LT}}$	`P[Form.Sph.1x25:SRC:LT]`
$P_{\mathrm{Size.Sph.1x25:SRC:LT}}$	`P[Size.Sph.1x25:SRC:LT]`
$P_{\mathrm{Form.Sph.1 \times 25:ODR:LT}}$	`P[Form.Sph.1 × 25:ODR:LT]`
$P_{\mathrm{Form.Sph.D95\,\%:ODR:LT}}$	`P[Form.Sph.D95 %:ODR:LT]`
$P_{\mathrm{Size.Sph.1 \times 25:ODR:LT}}$	`P[Size.Sph.1 × 25:ODR:LT]`
$P_{\mathrm{Size.Sph.All:ODR:LT}}$	`P[Size.Sph.All:ODR:LT]`
$E_{\mathrm{Form.Pla.D95\,\%:ODR:LT}}$	`E[Form.Pla.D95 %:ODR:LT]`
$P_{\mathrm{Form.Sph.}n\mathrm{x25::MPS.LT}}$	`P[Form.Sph.nx25::MPS.LT]`
$P_{\mathrm{Size.Sph.}n\mathrm{x25::MPS.LT}}$	`P[Size.Sph.nx25::MPS.LT]`
$L_{\mathrm{Dia.}n \times \mathrm{25::MPS.LT}}$	`L[Dia.n × 25::MPS.LT]`
$E_{\mathrm{Vol}:l:\mathrm{LT,MPE}}$ $E_{\mathrm{Bi}:l:\mathrm{LT,MPE}}$	`MPE(E[Vol:l:LT])` `MPE(E[Bi:l:LT])`
$P_{\mathrm{Form.Sph.1x25:SMR:LT,MPE}}$	`MPE(P[Form.Sph.1x25:SMR:LT])`
$P_{\mathrm{Form.Sph.1x25:SRC:LT,MPE}}$	`MPE(P[Form.Sph.1x25:SRC:LT])`
$P_{\mathrm{Form.Sph.1x25:ODR:LT,MPE}}$	`MPE(P[Form.Sph.1x25:ODR:LT])`
$P_{\mathrm{Size.Sph.1x25:SMR:LT,MPE}}$	`MPE(P[Size.Sph.1x25:SMR:LT])`
$P_{\mathrm{Size.Sph.1x25:SRC:LT,MPE}}$	`MPE(P[Size.Sph.1x25:SRC:LT])`
$P_{\mathrm{Size.Sph.1x25:ODR:LT,MPE}}$	`MPE(P[Size.Sph.1x25:ODR:LT])`
$L_{\mathrm{Dia.2x1:P\&R:LT,MPE}}$	`MPE(L[Dia.2x1:P&R:LT])`
$P_{\mathrm{Dia.15x1:SRC:LT,MPE}}$	`MPE(P[Dia.15x1:SRC:LT])`
$P_{\mathrm{Form.Sph.1x25:SRC:LT,MPE}}$	`MPE(P[Form.Sph.1x25:SRC:LT])`
$P_{\mathrm{Size.Sph.1x25:SRC:LT,MPE}}$	`MPE(P[Size.Sph.1x25:SRC:LT])`
$P_{\mathrm{Form.Sph.1 \times 25:ODR:LT,MPE}}$	`MPE(P[Form.Sph.1 × 25:ODR:LT])`
$P_{\mathrm{Form.Sph.D95\,\%:ODR:LT,MPE}}$	`MPE(P[Form.Sph.D95 %:ODR:LT])`

Table 5 *(continued)*

Symbol used in this document	Corresponding indication
$P_{\text{Size.Sph.1} \times \text{25:ODR:LT,MPE}}$	`MPE(P[Size.Sph.1 × 25:ODR:LT])`
$P_{\text{Size.Sph.All:ODR:LT,MPE}}$	`MPE(P[Size.Sph.All:ODR:LT])`
$E_{\text{Form.Pla.D95 \%:ODR:LT,MPE}}$	`MPE(E[Form.Pla.D95 %:ODR:LT])`
$P_{\text{Form.Sph.}n\text{x25::MPS.LT,MPE}}$	`MPE(P[Form.Sph.nx25::MPS.LT])`
$P_{\text{Size.Sph.}n\text{x25::MPS.LT,MPE}}$	`MPE(P[Size.Sph.nx25::MPS.LT])`
$L_{\text{Dia.}n \times \text{25::MPS.LT,MPE}}$	`MPE(L[Dia.n × 25::MPS.LT])`

Annex A
(informative)

Forms

A.1 Form 1 — General specifications and rated conditions

Rated operating conditions

Measurement Envelope					
Distance (Range)		Min.	____ m	Max.	____ m
Horizontal Angle (Azimuth)		Min.	____ °	Max.	____ °
Vertical Angle (Elevation / Zenith)		Min.	____ °	Max.	____ °
	or				
Length × width × height (Prismatic Volume)		____ m *by* ____ m *by* ____ m			
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.	____ Pa	Max.	____ Pa
d.	*Ambient Light:* The manufacturer shall identify conditions, if any, under which ambient light degrades specifications.				
e.	*Electrical*	Voltage	____ V	Current	____ A
		Frequency	____ Hz	Surge/sag	____ V
		Transient max.	____ V	Transient duration	____ s
f.	*Allowable orientations (vertical, horizontal, etc.)*	________			
g.	*Probe type:* The probe diameter and reflector type (e.g. in air SMR vs. solid prism SMR, or cat's eye) used during performance testing shall be specified.				
		Diameter	____ mm	Reflector type	________
h.	*Calibrated test length*				
	CTE	Min.	____ 10^{-6}/°C	Max.	____ 10^{-6}/°C
	CTE uncertainty			Max.	____ 10^{-6}/°C
i.	*Sampling Strategy:* The manufacturer shall state the measurement acquisition time (averaging time) and sampling frequency (points per second) to meet specification.				
		Acq. time	____ s	Frequency	____ points/s
j.	*Warm up time*	Warm up time	____ min		

Limiting conditions

k.	*Temperature Range*	Min.	____ °C	Max.	____ °C
l.	*Humidity Range*	Min.	____ % RH	Max.	____ % RH
m.	*Barometric Pressure Range*	Min	____ Pa	Max.	____ Pa

A.2 Form 2 — Manufacturer's performance specifications

Errors in µm

Length errors	$E_{Vol:0:LT,\ MPE}$ or $E_{Bi:0:LT,\ MPE}$ Test value uncertainty Pass/fail
Thermal comp Errors	$E_{Vol:0:LT,\ MPE}$ E_{Therm} Test value uncertainty Pass/fail
Probing size and form errors	$P_{Size.Sph.1x25:SMR:LT,\ MPE}$ $P_{Size.Sph.1x25:SMR:LT}$ Test value uncertainty Pass/fail $P_{Form.Sph.1x25:SMR:LT,\ MPE}$ $P_{Form.Sph.1x25:SMR:LT}$ Test value uncertainty Pass/fail
Location errors	$L_{Dia.2x1:P\&R:LT,\ MPE}$ $L_{Dia.2x1:P\&R:LT}$ Test value uncertainty Pass/fail
Test performed by Date Serial number Final test results (pass/fail)	

As different MPEs are permitted for different tests, this table may be extended to accommodate the complete specification.

☐ Check here if calibrated test lengths are bi-directional (`E[Bi:0:LT]`)

☐ Check here if calibrated test lengths are averaged (`E[Vol:0:LT]`)

☐ Check here if specification corresponds to the laser tracker mounted in other than vertical orientation of the standing axis

NOTE For explanation of E_{Therm} see Annex C.

Subclause 6.4 requires that the MPEs for calibrated test lengths be explicitly stated in a table. An example of such a table is given in Figure A.1.

For lengths required by this document to be in the range 2,25 m to 2,75 m, give the MPE for 2,75 m.

For lengths recommended by this document to be in the range 7 m to 9 m, give the MPE for 9 m.

Formula for MPEs 1–35 and 41			Any format	
Formula for ranging MPEs (positions 36–40)			Any format	
Additional MPE formulas (if any)			Any format	
Additional MPE formulas (if any)			Any format	
Test length position	**MPE**		**Test length position**	**MPE**
1			**22**	
2			**23**	
:			**:**	
:			**:**	
:			**41**	
21				

☐ Check here if calibrated test lengths are bi-directional (`E[Bi:0:LT]`)

☐ Check here if calibrated test lengths are averaged (`E[Vol:0:LT]`)

☐ Check here if specification corresponds to the laser tracker mounted in other than vertical orientation of the standing axis

Figure A.1 — Example of table for stating MPEs

Length 41 is the workpiece thermal compensation test. It is performed over a length of 15 m and should meet the MPE generated by the formula for lengths 1 to 35.

Annex B
(normative)

Calibrated test lengths

B.1 General

The measurand of interest (in the error of length measurement test) is a point-to-point distance in space. The realization of this measurand is accomplished using calibrated test lengths, where the distance between two physical points is traceable to the SI unit of length. Examples of this realization are given in Table B.1. The distinction between averaged and bi-directional lengths is discussed in B.6.

B.2 Material measures

The measurand is the length of the material measure, such as a gauge block, step gauge or ball bar.

These may be the same as in ISO 10360-2. Ball bars and step gauges may either be averaged or bi-directional in nature. Gauge blocks are always measured in a bi-directional manner.

B.3 Scale bars

The measurand is the centre-to-centre distance of spheres in the bar's nests.

These are averaged test lengths. Care should be used when the nests result in the sphere centres being off the neutral axis of the test length.

B.4 Rigid nests

The measurand is the centre-to-centre distance between spheres in fixed nests.

These are averaged measurements taken on nests mounted on permanent or semi-permanent monuments or structural members (e.g. walls, pillars) of a building in which testing occurs.

The calibration of nest-to-nest distances is often done with an independently calibrated interferometer. It is permissible to use a tracking interferometer for this purpose.

B.5 Rail or carriage system

The measurand is the distance between two different instances of a single sphere, nest or gauge block at different locations along the rail.

These measurements can either be averaged or bi-directional, depending on the probing strategy and the geometry of the moving object.

B.6 Averaged and bi-directional lengths

Tests for the error of length measurement for many coordinate measuring systems use bi-directional lengths for the determination of errors. As the realization of long bi-directional lengths can be both difficult and expensive, it is common to establish point-to-point distances as averaged lengths between nests.

If the manufacturer wishes to specify averaged tests, $E_{\mathrm{Vol:0:LT}}$ shall be used.

An estimate of bi-directional length errors (e.g. when using the SMR sensor) can be calculated with Formula (B.1).

$$E_{\text{Bi:0:LT}} \approx E_{\text{Vol:0:LT}} + P_{\text{Size.Sph.1x25:SMR:LT}} \tag{B.1}$$

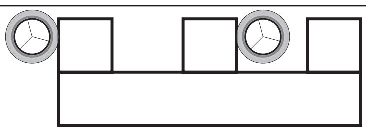
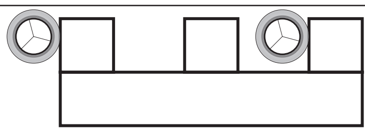
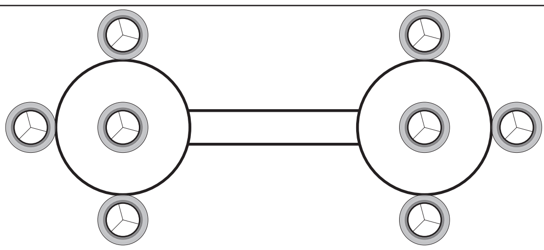
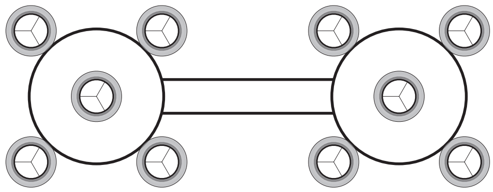
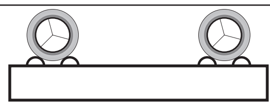
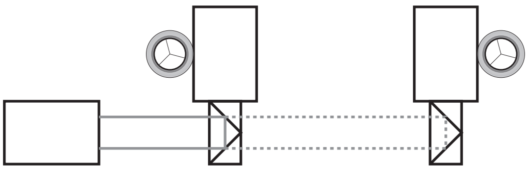
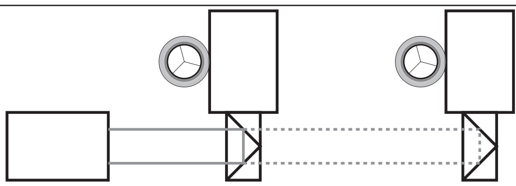
By mutual agreement, the following inequalities can be used establishing comformity or non-comformity of a length measurement to bi-directional length-measuring specifications.

If $-E_{\text{Bi:0:LT, MPE}} <= E_{\text{Vol:0:LT}} + \text{P}_{\text{Size.Sph.1x25:SMR:LT}} \leq E_{\text{Bi:0:LT, MPE}}$, then the specification is met.

If $E_{\text{Vol:0:LT}} < -E_{\text{Bi:0:LT, MPE}}$ or $E_{\text{Vol:0:LT}} > E_{\text{Bi:0:LT, MPE}}$, then the specification is not met.

If the user is not satisfied with using these inequalities, a bi-directional calibrated test length should be obtained for testing.

Table B.1 — Realization of bi-directional and averaged lengths

	Bi-directional lengths	**Averaged lengths**
Gauge Block		
Step gauge		
Ball bar		
Scale bar		
Laser rail		
Rigid nests		

Annex C
(normative)

Thermal compensation of workpieces

Because of the large size of many workpieces measured with laser trackers, the correct operation of the workpiece temperature measurement and compensation system is critical to accurate measurement.

For this purpose, a “synthetic” test length is measured, which is nominally 15 m long. With a calibrated reference interferometer, which is traceable and which may also be the calibrated interferometer of a second laser tracker, a calibrated test length between two target nests is established. Air temperature, air pressure and air humidity are measured by the weather station of the reference interferometer and, thus, the refractive index of the air is determined and the refractive index of the test length compensated. The measurement result is the calibrated length L of the test length. The length L is now used to calculate a synthetic test length L_S, equivalent to the length of a gauge block with the thermal expansion coefficient of exactly $\alpha_S = 11{,}5 \times 10^{-6}$ / °C. The effect of this calculation is that the test length is being changed in such a way that it corresponds to a length with a thermal expansion coefficient of $11{,}5 \times 10^{-6}$/°C, as shown in Formula (C.1).

$$L_S = L[1 - \alpha_S\,(T - 20\,°\text{C})] = L[1 - (11{,}5 \times 10^{-6})\,(T - 20\,°\text{C})] \quad \text{(C.1)}$$

The test length temperature T required for the calculation is measured with a calibrated thermometer on a piece of steel (a specimen) and *not* with the aid of any temperature-measuring system delivered with the laser tracker. The specimen shall be in thermal equilibrium with its environment, and the test shall be performed when the temperature T is more than 1 °C away from 20 °C, i.e. $|\,T - 20\,°\text{C}\,| > 1\,°\text{C}$. After that, the synthetic test length between the two target nests is measured with the laser tracker to be tested. For this purpose, it is recommended that the laser tracker is installed at a short distance and directly aligned to the test length (i.e. the measurement is performed radially). A thermal expansion coefficient, $\alpha_S = 11{,}5 \times 10^{-6}$/°C, shall be entered for the test length. For the laser tracker, the calibrated test length thus seems to be made of steel. To compensate the thermal expansion of the test length, the temperature of the same specimen, which is still in thermal equilibrium with its environment, is measured – as above, but this time with the laser tracker's sensor – to obtain the test length temperature. If the laser tracker being tested in not equipped with a workpiece temperature sensor, no manual compensation of the measured length L is permitted. The measurement of the synthetic test length with the laser tracker is repeated three times with the result L.

The error $E_{\text{Therm}} = (L - L_S)$ is calculated for each of the three measurements. None of these errors shall exceed $E_{\text{Vol:0:LT, MPE}}$ for the 15 m test length.

When the manufacturer does not provide software with the laser tracker, they shall specify an $E_{\text{Vol:0:LT, MPE}}$ for those third-party software systems with which their instrument will be used with temperature compensation.

Annex D
(informative)

Specification of MPEs

D.1 General

The errors that are present in using laser trackers to measure point-to-point distances do not result in a simple linear relationship between the length measured and the error in determining that length. For this reason, the manufacturer is permitted to specify laser tracker performance using a more complex formula. The subsystem contributors and a resulting generic formula are given in this annex.

D.2 Subsystem contributions

The notation for the manufacturer-supplied performance specifications (of the subsystems) for a laser tracker is given in Table D.1.

In Table D.1, the quantity R refers to the distance between the laser tracker and the point in space where a point coordinate is measured. The laser tracker manufacturer specifies the rated conditions (see Annex A) within which the MPE specifications hold. Accordingly, subsystem specifications, as shown in Table D.1, include the effects of measurement errors resulting from environmental conditions that are allowed by the rated conditions.

In some cases, the manufacturer may state additional subsystem specifications that can include environmental conditions as parameters in their MPE specification formula. The e_{IFM} and e_{ADM} specifications refer to the basic capability of the ranging system, while e_{R0} and e_{T} relate to the geometry of the laser tracker assembly and the quality of the rotary encoders.

Table D.1 — Errors related to laser tracker performance

Laser tracker subsystem	Symbol	Form of error contribution[a]	Formula
Interferometer	e_{IFM}	$e_{\mathrm{IFM}} = A_{\mathrm{IFM}} + B_{\mathrm{IFM}}R$	(D.1)
Absolute distance meter	e_{ADM}	$e_{\mathrm{ADM}} = A_{\mathrm{ADM}} + B_{\mathrm{ADM}}R$	(D.2)
Laser tracker origin	e_{R0}[b]	$e_{\mathrm{R0}} = A_{\mathrm{R0}}$	(D.3)
Transverse	e_{T}[c]	$e_{\mathrm{T}} = A_{\mathrm{T}} + B_{\mathrm{T}}R$	(D.4)

[a] A_{IFM}, A_{ADM} and A_{R0} are constant values expressed in micrometres; B_{IFM} and B_{ADM} are dimensionless constant values.

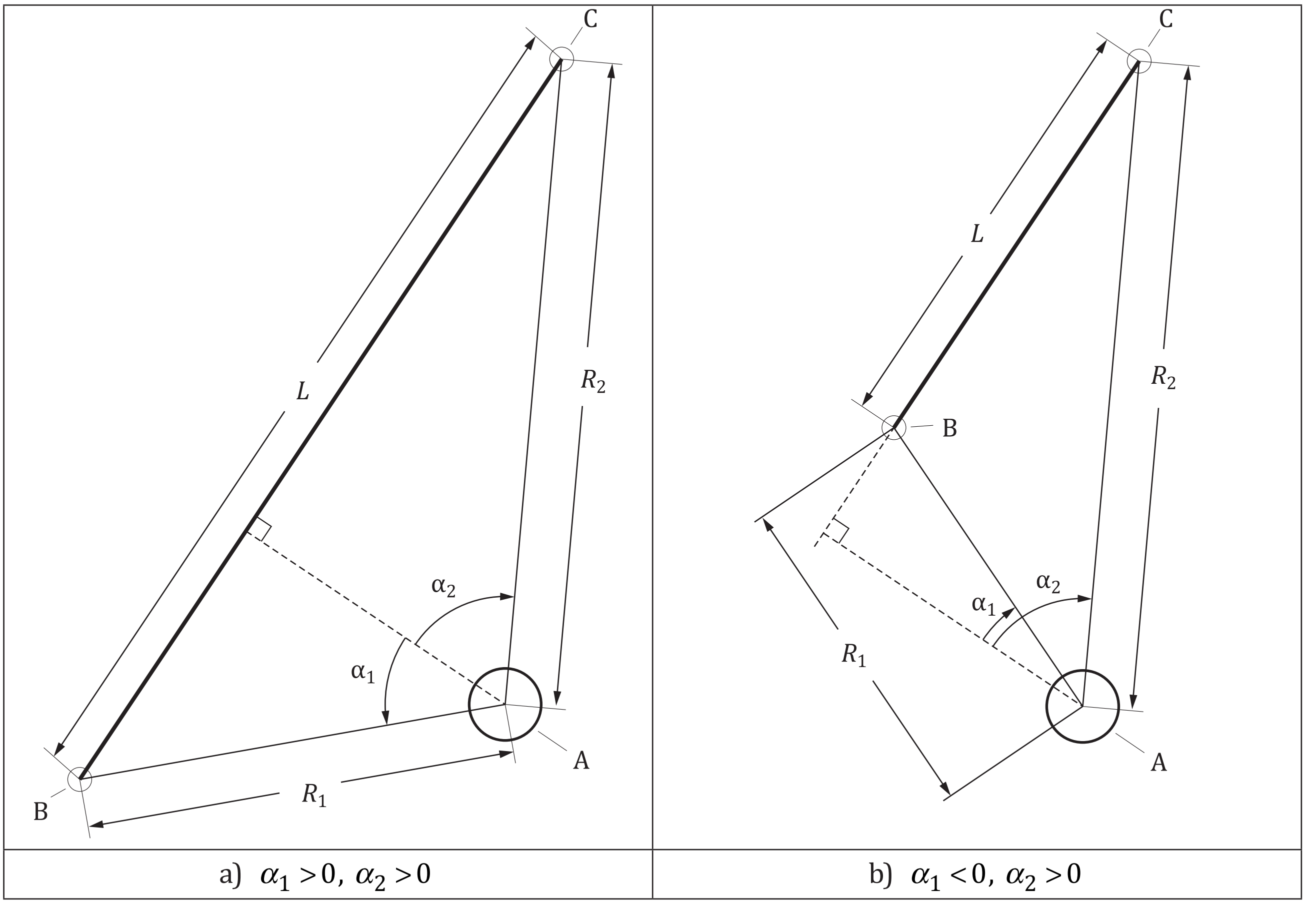
[b] This error is seen most clearly when comparing the measurement of L shown in Figure D.2 with a measurement of L obtained by placing the laser tracker directly between point 1 and point 2 of Figure D.2

[c] Transverse error refers to the error resulting from incorrectly determining the angular components in determining the location of a measured point.

D.3 Development of generic formula

The geometrical arrangement of a laser tracker that measures the coordinates of points 1 and 2 for many of the positions described in Clause 6, Table 4, is shown in Figure D.1; see Figure D.2 for cases where the laser tracker is located on a line defined by the measured test length. From these coordinates, the test length L is determined.

The MPE for this length measurement is specified by the manufacturer for performance-verification tests. One method of expressing the MPE of measured test length L is using Formula (D.5). In this formula, the quantities that contain the subscripts 1 or 2 refer to the error contributions when evaluated at the pair of points 1 and 2 (respectively) for either the IFM mode or ADM mode specifications in Table D.1, depending on whether the IFM mode or ADM mode is used.



Key

A laser tracker (top view)

B point 1

C point 2

Figure D.1 — Geometric relationship between test length and laser tracker

$$E_{\text{Vol:L:LT,MPE}} = \left(e_1^2 sin^2\alpha_1 + e_2^2 sin^2\alpha_2 + e_{\text{R0}}^2 (sin\alpha_1 + sin\alpha_2)^2 + e_{\text{T1}}^2 cos^2\alpha_1 + e_{\text{T2}}^2 cos^2\alpha_2 \right)^{\frac{1}{2}} \quad \text{(D.5)}$$

where

α_1 is the angle to the first point from the perpendicular to the test length;

α_2 is the angle to the second point from the perpendicular to the test length;

e_1 is the distance measuring contribution for the first point;

e_2 is the distance measuring contribution for the second point;

e_{R0} is the laser tracker origin contribution;

e_{T1} is the transverse measuring contribution for the first point;

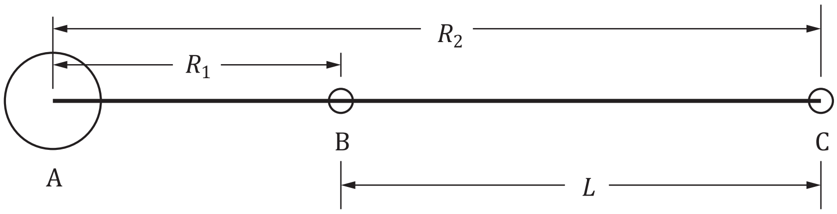
e_{T2} is the transverse measuring contribution for the second point.

The angles α_1 and α_2 are positive in the directions shown in Figure D.1 a) and negative in the opposite directions, as is the case for α_1 in Figure D.1 b). The quantities e_1, e_2, e_{R0}, e_{T1} and e_{T2} are calculated using Formulae (D.1) to (D.4), where the quantity R in the $A + BR$ formula refers to the distance R_1 or R_2. The subscript 1 refers to path 1 and the subscript 2 refers to path 2. So, for example, $e_{T1} = A_T + R_1 \times B_T$ and e_1 is e_{IFM} or e_{ADM} for path 1.

Formula D.5 shows the MPE having no environmental (e.g. temperature-related) dependence. If the MPEs are specified in this way, then the MPE values apply to any environment satisfying the rated operating conditions (e.g. Clause 5 and Annex A) while employing reasonable, good practices for measurement (e.g. 5.2). It is possible to express the MPE formula in a more complicated manner, showing specific temperature-related dependence, but for testing this would require the ability to measure the varying temperature along the beam path at the time of each measurement.

D.4 Note on distance (range) testing

A special case is when the laser tracker is aligned with the test length. That is, the case of a measurement in which the laser tracker is aligned with points 1 and 2, as shown in Figure D.2.



Key

A laser tracker (top view)

B point 1

C point 2

Figure D.2 — Laser tracker arrangement for collinear measurement

Point 1 establishes one end of the test length for the laser tracker measurement and point 2 the other end of the test length. Under these conditions, the two coordinate measurements are correlated, permitting Formula (D.5) to be rewritten as Formula (D.6):

$$E_{Vol:L:LT,MPE} = A_{mode} + (B_{mode} \times R_2 - B_{mode} \times R_1) = A_{mode} + B_{mode} \times L \quad (D.6)$$

where

A_{mode} is the constant term from Formula (D.1) or (D.2);

B_{mode} is the dimensionless constant from Formula (D.1) or (D.2);

R_1 is the distance to the first point;

R_2 is the distance to the second point;

L is the distance from point 1 to point 2.

NOTE “mode” refers to either IFM mode [Formula (D.1)] or ADM mode [Formula (D.2)] from Table D.1.

In Formula (D.6), the length is equal to the distance between the end points of the test length; in other words, $L = R_2 - R_1$.

D.5 Note on two-face measurement

Another special case is that of the two-face measurement. In this measurement, two points are measured in different modes (frontsight and backsight, where frontsight is the normal measuring mode). To put the laser tracker in backsight mode, the azimuth angle is changed by approximately 180° and the elevation angle is changed to point the laser beam back at the target. The transverse distance, perpendicular to the beam path, between the frontsight and backsight coordinates is the location error. The two-face test is a challenging test of laser tracker performance because most of the laser tracker transverse errors are doubled. The two-face MPE (denoted $L_{\text{Dia.2x1:P\&R:LT, MPE}}$) is equal to twice the value of e_{T1}.

Annex E
(informative)

Interim testing

E.1 General

Interim testing is designed to ensure that a measurement system is functioning properly between routine calibrations. Interim test procedures are expressly designed to be sensitive to changes in a measurement system that has the potential to degrade performance to a degree that invalidates the manufacturer's performance specifications. Interim testing is not a substitute for routine calibration or error compensation. The single most effective interim test of the laser tracker's correct operation and compensation is the two-face test, described in 6.3. The performance of the additional tests in this subclause may additionally be used to provide confidence in the operation of the laser tracker.

This annex provides an interim test to assess the performance of a laser tracker in the field. There are two parts to this interim test: the first part (E.5.1) describes a procedure to assess the extent of optical and geometrical misalignments in the laser tracker while the second part (E.5.2) describes a procedure to assess the inclinometer errors in the laser tracker. Depending on the needs of the user, either or both parts may be performed.

E.2 Environmental considerations

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

E.3 Frequency of interim testing

The frequency of interim testing is a matter of economics and necessity, i.e. the time period between interim tests should be chosen in a manner that meets the needs of the measurement system user while not compromising the integrity of the measurement tasks performed. This is a judgment call on the part of the user. A laser tracker that is in a stable environment with a single user will typically need interim testing less often than one that is frequently transported, used by multiple operators, or in a harsh environment. The frequency of testing is also strongly affected by balancing the cost of interim testing against the consequences of accepting a bad workpiece or rejecting a good one. It may be useful to consider the interim testing interval as a percentage of total laser tracker operating hours. Some users with high-value and/or safety-critical workpieces may elect to perform daily tests, while other users will possibly test weekly or monthly. Additionally, interim testing should be conducted after any sort of significant event such as the laser tracker being subject to excessive vibrations or to potential damage.

E.4 A best practice guideline

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

E.5 Interim test procedure

E.5.1 Interim test for geometry errors

E.5.1.1 Introduction

The interim test for geometry errors comprises two-face tests and length measurement tests performed at different positions of the test length with respect to the laser tracker. The objective of this interim test is to assess the performance of the laser tracker in the presence of geometrical or optical misalignments such as those occurring due to frequent packing, transport and unpacking of a laser tracker. These causes of misalignments typically affect the geometry parameters of a laser tracker but do not affect the ranging unit. Thus, the calibration of the reference artefact (such as a scale bar or a collection of fixed nests) used for this test may be performed using the ranging system of the laser tracker that is under test, as described in D.4. More information on this interim test and the error sources to which these tests are sensitive can be found in Reference [10].

Because interim testing and laser tracker reverification testing are procedures set by the laser tracker user, the user may assign different laser tracker specifications and decision rules for reverification and interim testing than for acceptance testing. Thus, a ‘simple acceptance and rejection’ decision rule with a capability index C_m equal to or greater than 4 may be used in accordance with 8.3. That is, the expanded uncertainty U of the calibrated test length used in the interim testing should not exceed one-quarter of the MPE of the length measurement tests described in E.5.1.2. Other decision rules may also be used. While the user is permitted to state the relevant MPE values for these tests, the MPE formulas specified for evaluating the performance tests of 6.2 may be considered when determining the MPEs of the interim tests.

E.5.1.2 Procedure

For the purposes of illustration, the interim test procedure is described here using a three-nest scale bar as shown in Figure E.1; other methods of realizing the test are briefly described in E.5.1.3. The three-nest scale bar has one nest (nest B) located at the centre of the scale bar while the other two nests (nests A and C) are located at the ends. The length of the scale bar, which is the distance from nest A to nest C, should be at least 2,25 m (as per 6.4.3).

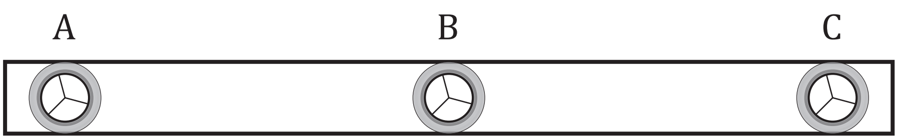
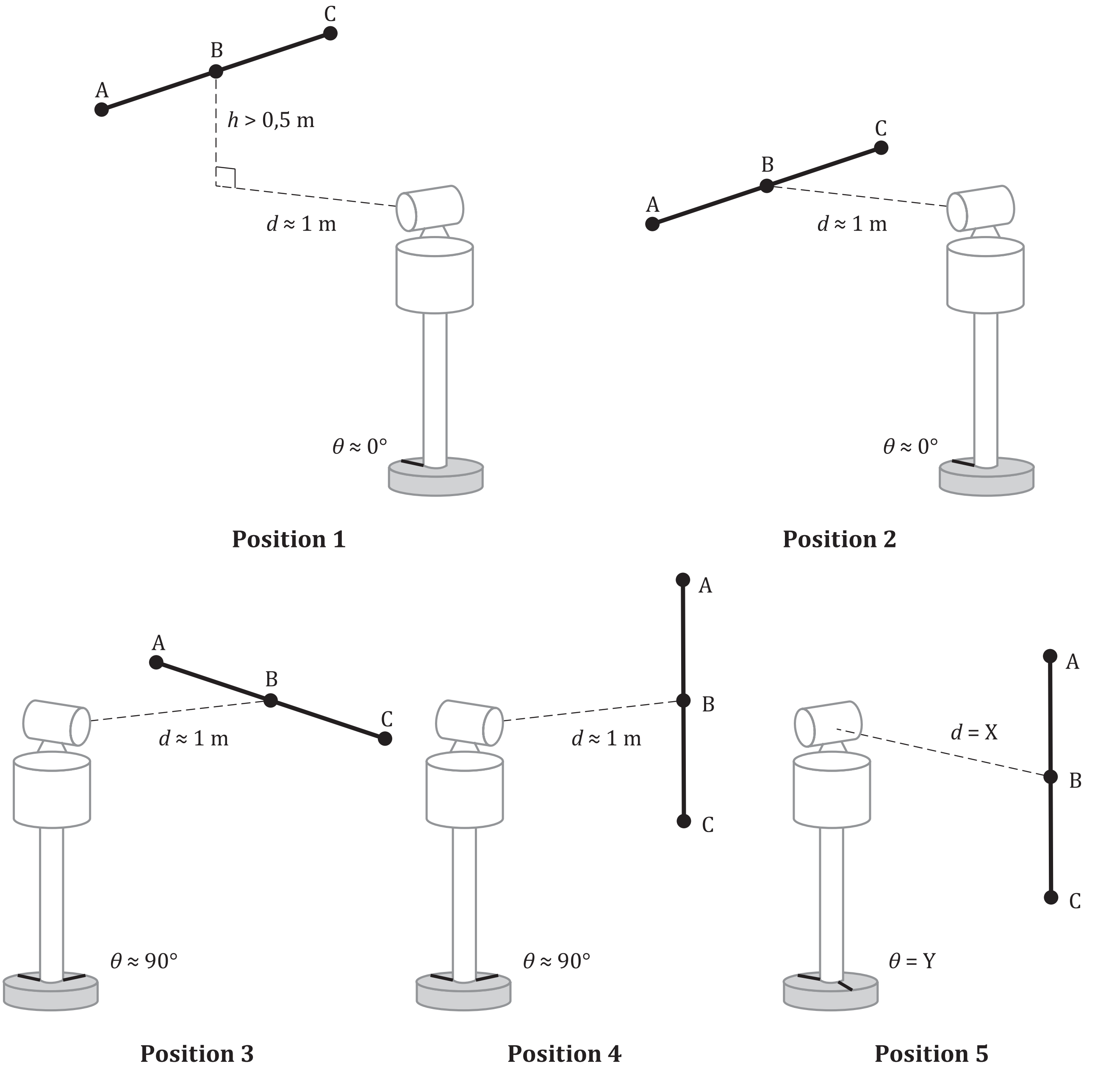


Figure E.1 — Scale bar with three nests for interim testing

The test procedure requirements are as follows:

— For each of the five positions in Figure E.2, three length measurement errors are determined. One length measurement error corresponds to a symmetrical (relative to the laser tracker) length AC. Two length measurement errors correspond to asymmetrical lengths AB and BC. All length measurement errors are calculated using data acquired from the front-face of the laser tracker only.

— For each of the five positions in Figure E.2, three two-face errors (one at each nest) are determined.



Key

X user-selected *d*

Y any azimuth angle *θ*

Figure E.2 — Five test positions to perform the interim check of laser tracker (0° for reference only)

In Figure E.2, nest B is located directly in front of the laser tracker so that the line joining the laser tracker and nest B is orthogonal to the line joining the three nests A, B and C. For all positions, length AC should be at least 2,25 meters, and lengths AB and BC should be approximately equal. For positions 1, 2 and 3, nests A and C are located on either side of nest B so that the nests A, B and C form a horizontal line. For positions 4 and 5, nests A and C are located on either side of nest B so that the nests A, B and C form a vertical line.

The five positions of the interim test procedure are given in the following list. The azimuth angles of 0° and 90° in the list (and in Figure E.2) are for reference only and any pair of azimuth angles differing by 90° is allowed.

1) Scale bar in the horizontal orientation, nest B at least 0,5 m above the laser tracker and the laser tracker at 0° azimuth when facing the centre of the scale bar, and located at a distance *d* (as close as practical, preferably 1 m) from the scale bar.

2) Scale bar in the horizontal orientation, nest B at laser tracker height and the laser tracker at 0° azimuth when facing the centre of the scale bar, and located at a distance *d* (as close as practical, preferably 1 m) from the scale bar.

3) Scale bar in the horizontal orientation, nest B at laser tracker height and the laser tracker at 90° azimuth when facing the centre of the scale bar, and located at a distance *d* (as close as practical, preferably 1 m) from the scale bar.

4) Scale bar in the vertical orientation, nest B at laser tracker height and the laser tracker at 90° azimuth when facing the centre of the scale bar, and located at a distance *d* (as close as practical, preferably 1 m) from the scale bar.

5) Scale bar in the vertical orientation, nest B at laser tracker height and the laser tracker placed at any azimuth angle and distance as determined by the user. Both the azimuth angle and the distance *d* should be different from that employed in position 4.

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

E.5.1.3 Alternative ways of realizing the interim test for geometry errors

While the interim test procedure for laser tracker geometry errors is described earlier using a three-nest scale bar, the test may be performed in other ways as well. For example, a two-nest scale bar that is at least 2,25 m long may be used to realize the symmetrical and asymmetrical lengths for each of the five positions by either moving the laser tracker or the scale bar. A set of nests fixed to a rigid structure (such as a wall) where the distance between the nests has been previously calibrated may also be used for the interim tests.

E.5.2 Interim test for inclinometer errors (orient to gravity tests)

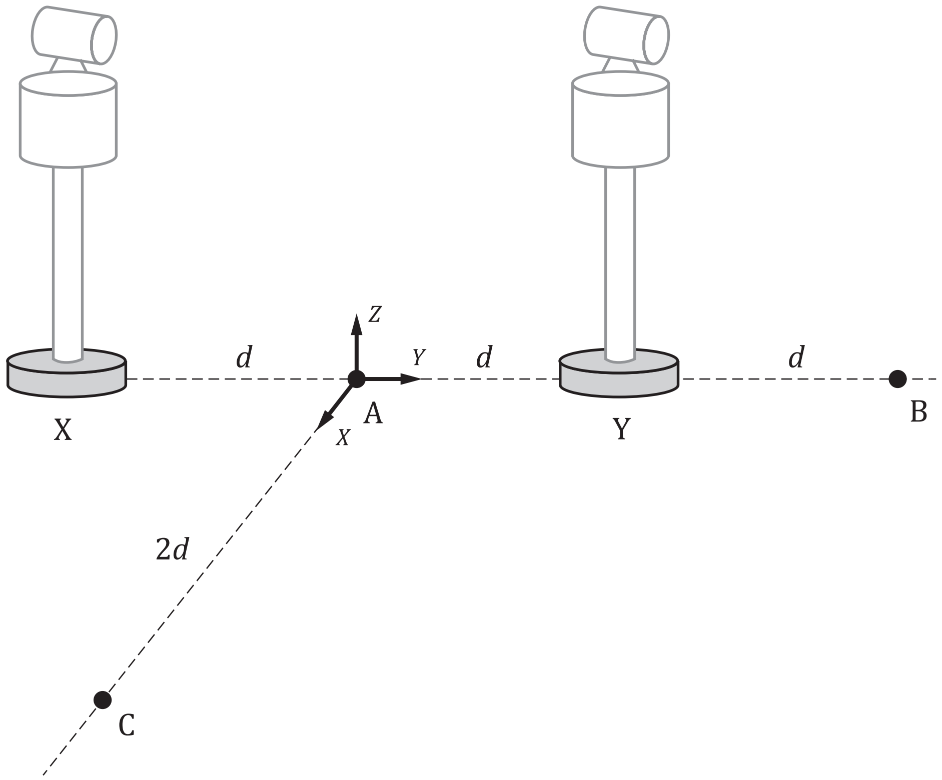
E.5.2.1 Introduction

This subclause describes an interim test procedure to determine the performance of the laser tracker's inclinometer sensor. There are two modes in which inclinometers are used in laser trackers. In the first and more common mode of usage, inclinometers are used to first establish a gravity-aligned coordinate system in which all subsequent test object measurements are performed. In this mode of usage, the inclinometer is not read as part of every object coordinate measurement. The test for this first mode is described in E.5.2.3. In the second mode of usage, inclinometer is read as part of each object coordinate measurement, and the measured coordinate is transformed to a gravity aligned coordinate system based on the current measurements of the tilt angles. The test for the second mode is described in E.5.2.4. While the interim test for both modes of usage involves the laser tracker and three stationary nests mounted on the ground, there are differences in the test procedure. The test set-up and procedures are described next.

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

E.5.2.2 Set-up

The set-up for both interim tests for inclinometer errors is as follows. Two nests, A and B, are placed on the floor, a distance 2*d* apart from each other as shown in Figure E.3. The value for the distance *d* is recommended to be at least 1 m and not larger than 5 m. The laser tracker is placed on the line joining the nests A and B, either outside at position 1 or inside at position 2. Positions 1 and 2 are at a distance *d* from nest A on the line joining the nests A and B. Target C is placed on the floor so that AC is perpendicular to AB and the distance AC is *2d*. The laser tracker positions should not deviate from the line AB by an amount larger than 0,1 m. Similarly, the nest C should not deviate from its recommended location (on the *X* axis in Figure E.3) by an amount larger than 0,1 m.



Key

X position 1

Y position 2

Figure E.3 — Set-up for inclinometer tests

E.5.2.3 Inclinometer test based on laser tracker tilt

For the first mode of inclinometer usage, as described above, the test procedure involves measuring the *Z* coordinates of targets distributed on the floor in a gravity-aligned coordinate system. The laser tracker is then slightly tilted, a new gravity-aligned coordinate system is constructed and the targets are measured again. The *Z* coordinates of the targets should remain the same if there are no inclinometer errors. To determine the magnitude of inclinometer errors, the difference in *Z* coordinates before and after tilt are converted to units of angle and compared against manufacturer provided MPEs. Because the laser tracker is tilted by a small amount while located at the same position, the errors in the vertical angle are expected to remain constant before and after tilt; thus, the differences in the *Z* coordinates may be attributed entirely to the inclinometer errors.

The test procedure is as follows:

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

2) Measure the SMRs located at the nests A, B and C in the level-frame coordinate system.

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

4) Rotate the coordinate system so that nest B lies on the *YZ* plane; ensure that the *Z* axis continues to remain aligned with the gravity direction.

5) Record the *Z* coordinate of points B and C, Z_{B1} and Z_{C1} as measured by the laser tracker in the coordinate system established in step 4.

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

7) Establish a new level-frame so that the *Z* axis is once again aligned with the gravity direction.

8 to 10) Repeat steps 2 to 4.

11) Record the *Z* coordinate of points B and C, Z_{B2} and Z_{C2} as measured by the laser tracker in the coordinate system established in step 4.

12) Calculate the errors, ΔZ_B and ΔZ_C, determined as the difference in the *Z* coordinates of points B and C before and after tilt, i.e. $\Delta Z_B = Z_{B2} - Z_{B1}$ and $\Delta Z_C = Z_{C2} - Z_{C1}$.

13) Convert the errors in Z heights to angular units, $e_B = \Delta Z_B/(2d)$ and $e_C = \Delta Z_C/(2d)$.

14) Compare these errors against manufacturer-specified MPEs for the inclinometer error in units of angle. The laser tracker has passed the test if e_B < MPE and e_C < MPE.

NOTE In each case above, the coordinate system that results is aligned with gravity (z axis), the origin at point A and having point B in the YZ plane (approximately on the y-axis).

E.5.2.4 Inclinometer test based on laser tracker translation

For the second mode of inclinometer usage, there is an additional error source that scales with the distance to the target. This error source can be detected by measuring two targets A and B from within the line AB, and again from outside the line AB, in a manner similar to that adopted for optical levels. However, by moving the laser tracker from position 1 to position 2 (or vice versa), the test convolves any inclinometer errors with errors in the vertical angle encoder. It should therefore be cautioned that the MPE for the inclinometer test based on laser tracker translation may be larger than the MPE for the inclinometer test based on laser tracker tilt (see E.5.2.3).

The test procedure is as follows:

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

2) Measure the SMRs located at the nests A, B and C in the level-frame coordinate system.

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

4) Rotate the coordinate system so that nest B lies on the *YZ* plane; ensure that the *Z* axis continues to remain aligned with the gravity direction.

5) Record the *Z* coordinate of points B and C, Z_{B1} and Z_{C1} as measured by the laser tracker in the coordinate system established in step 4.

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

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

8 to 10) Repeat steps 2 to 4.

11) Record the *Z* coordinate of points B and C, Z_{B3} and Z_{C3} as measured by the laser tracker in the transformed coordinate system.

12) Calculate the errors, ΔZ_B and ΔZ_C, determined as the difference in the *Z* coordinates of points B and C, before and after tilt, i.e. $\Delta Z_B = Z_{B3} - Z_{B1}$ and $\Delta Z_C = Z_{C3} - Z_{C1}$.

13) Convert the errors in *Z* heights to angular units, $e_B = \Delta Z_B/(2\mathrm{d})$ and $e_C = \Delta Z_C/(2d)$.

14) Compare these errors against manufacturer-specified MPEs in units of angle. The laser tracker has passed the test if e_B < MPE and e_C < MPE.

NOTE In each case above, the coordinate system that results is aligned with gravity (z axis), the origin at point A and having point B in the YZ plane (approximately on the y-axis).

E.5.2.5 Additional notes

There is an advantage to performing the test described in E.5.2.4 for all laser trackers regardless of the mode of inclinometer usage. The eccentricity of the vertical angle encoder along the vertical axis is not captured with adequate sensitivity through tests described in E.5.2. By taking advantage of the lever arm obtained by moving the laser tracker from position 1 to position 2, the test is sensitive to this error source with a considerably larger sensitivity. However, as mentioned earlier, the test convolves this error source with the inclinometer errors; thus, the ability to detect vertical angle encoder eccentricity is limited by the accuracy of the inclinometer.

Annex F
(normative)

Testing of a stylus and retroreflector combination (SRC)

F.1 General

There are two metrological results that are important in providing confidence in measurements taken with an SRC. The first of these is a test of the system when this probing method is used, and the second is a test of the registration of this probing method to the default (SMR) probing system.

The methods described in this annex intentionally reflect other parts of the ISO 10360 series, and intend to refine, not change, these existing methods. The symbols associated with the tests in this annex are given in Table F.1.

A simplified arrangement – consisting only of the stylus and retroreflector of the SRC – is shown in Figure F.1.

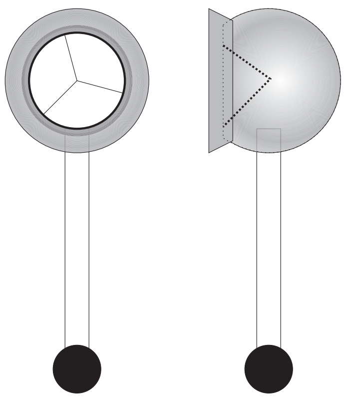


Figure F.1 — SRC (simplified)

F.2 Probing errors

The probe test for the SRC follows 6.2. Two tests are performed, at the locations described in Table 2. The values for $P_{\text{Form.Sph.1x25:SRC:LT}}$ and $P_{\text{Size.Sph.1x25:SRC:LT}}$ are found and compared to their respective MPEs.

F.3 Orientation-dependent errors

F.3.1 General

Different orientations of the SRC may result in the stylus having the same measurement point [C in Figure 2 b)]. This allows the measurement of a single point with many different orientations of the SRC. Two tests are performed, at the locations described in Table 2.

NOTE Orientation of the SRC refers to the roll, pitch and yaw of the SRC relative to the incoming beam from the laser tracker. These are not to be confused with the azimuth and elevation angles of the laser tracker.

F.3.2 Measuring equipment

A nest is used for this test that is of suitable size to accommodate the stylus used with the SRC. It is rigidly fixtured so that a range of SRC orientations will be measurable by the laser tracker.

F.3.3 Procedure

For each of the two test locations for the nest, five measurement points are taken with the SRC as shown in Figure F.2 (roll of the SRC). An additional five points are taken with the SRC rotating toward and away from the laser tracker (pitch of the SRC), and five more rotating the SRC about the stylus orientation unit vector (yaw of the SRC). The positions of the reflector should be widely spread over the access permitted by the nest for the roll tests and should also span at least 66 % of the stated acceptance angle for the retroreflector (and ancillary components, such as LEDs) in the pitch and yaw tests.

The manufacturer may specify the limits of roll for testing, but these shall be no less than ± 45°.

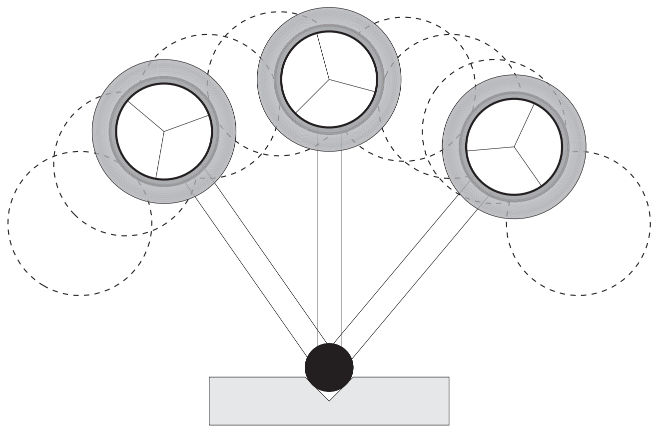


Figure F.2 — The orientation test for the SRC

F.3.4 Derivation of test results

The 15 measurement points are all of the same physical location. The ability of the instrument to locate all points in the same location is being tested. For this reason, the diameter of the minimum circumscribing sphere that contains all of the measured points is calculated. The diameter of this sphere is labelled $P_{\text{Dia.15x1:SRC:LT}}$.

F.4 Registration errors

The registration of the SRC to the main SMR probe shall follow the method of ISO 10360-9. A test sphere is measured with both the SRC and the SMR as shown in Figure F.3. Quantities to be measured include multiple probing system form error, $P_{\text{Form.Sph.2x25::MPS.LT}}$, multiple probing system size error, $P_{\text{Size.Sph.2x25::MPS.LT}}$, and multiple probing system location value, $L_{\text{Dia.2x25::MPS.LT}}$. The measured values are compared to specifications provided by the manufacturer, $P_{\text{Form.Sph.2x25::MPS.LT,MPE}}$, $P_{\text{Size.Sph.2x25::MPS.LT,MPE}}$ and $L_{\text{Dia.2x25::MPS.LT,MPE}}$, respectively, to determine conformity, as described in ISO 10360-9:2013, 7.1.

NOTE 1 The results can be expressed in the form $P_{\text{Size.Sph.2x25:SMR,SRC:MPS.LT}}$, and similarly for the other results.

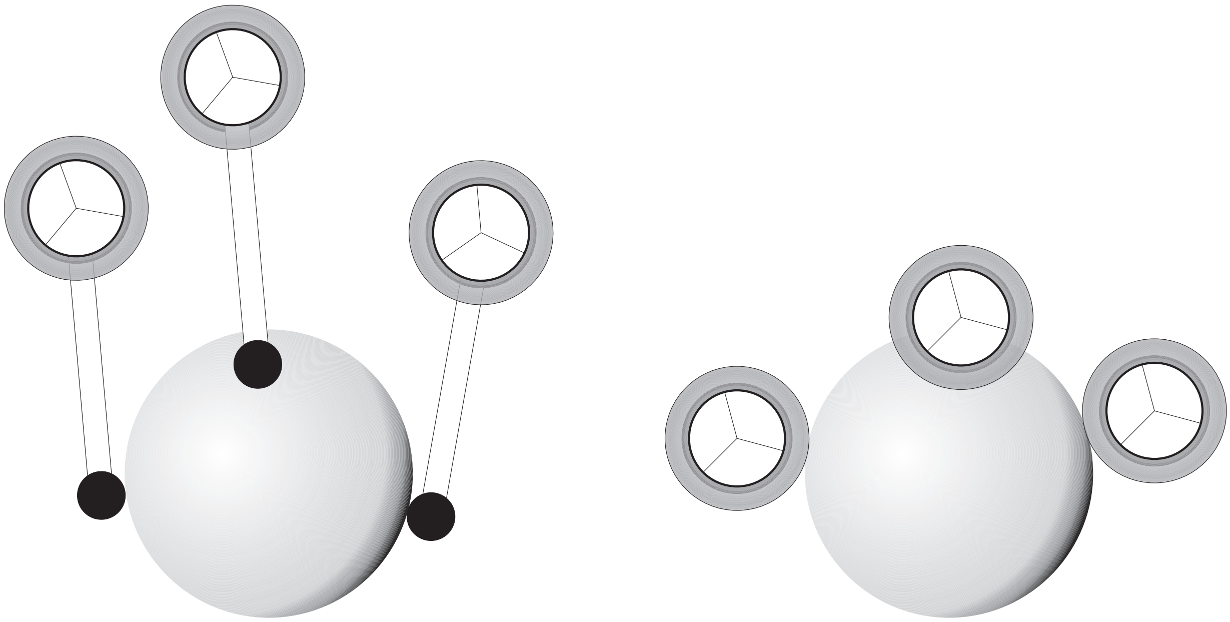


Figure F.3 — Multi-probe testing for SRC (left) and SMR (right)

NOTE 2 Only a few of the required 25 probing locations are shown in Figure F.3.

F.5 Symbols pertaining to this annex

Table F.1 — Quantities related to SRC tests

Symbol	Meaning
$P_{\text{Form.Sph.1x25:SRC:LT}}$	Probing form error for SRC
$P_{\text{Size.Sph.1x25:SRC:LT}}$	Probing size error for SRC
$P_{\text{Dia.15x1:SRC:LT}}$	Orientation error for SRC
$P_{\text{Form.Sph.1x25:SRC:LT,MPE}}$	Maximum permissible error of probing form for SRC
$P_{\text{Size.Sph.1x25:SRC:LT,MPE}}$	Maximum permissible error of probing size for SRC
$P_{\text{Dia.15x1:SRC:LT,MPE}}$	Maximum permissible error of orientation for SRC
$P_{\text{Form.Sph.}n\text{x25::MPS.LT}}$	Multiple probing system form error
$P_{\text{Size.Sph.}n\text{x25::MPS.LT}}$	Multiple probing system size error
$L_{\text{Dia.}n \times \text{25::MPS.LT}}$	Multiple probing system location error
$P_{\text{Form.Sph.}n\text{x25::MPS.LT,MPE}}$	Maximum permissible multiple probing system form error
$P_{\text{Size.Sph.}n\text{x25::MPS.LT,MPE}}$	Maximum permissible multiple probing system size error
$L_{\text{Dia.}n \times \text{25::MPS.LT,MPE}}$	Maximum permissible multiple probing system location error

Annex G
(normative)

Testing of an optical distance sensor and retroreflector combination (ODR)

G.1 General

Systems are available which collect points using an optical distance sensor (see Figure G.1), where the location and orientation of the optical distance sensor are determined using the laser tracker.

As in Annex F, there are two types of errors to be evaluated: probing errors and registration errors. The symbols associated with the tests in this annex are given in Table G.1.

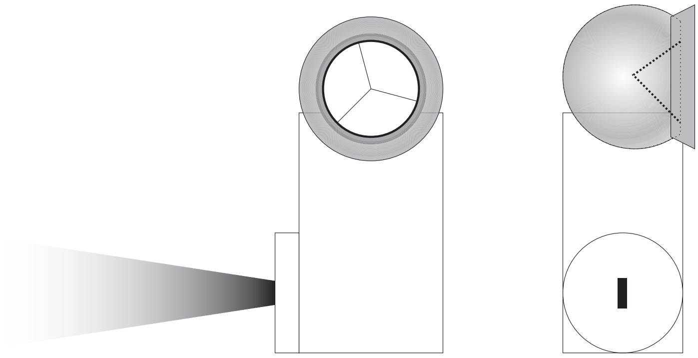


Figure G.1 — Simplified representation of the ODR

G.2 Probing errors

Measurements are performed according to ISO 10360-8:2013, 6.2. Quantities to be measured include probing form error, $P_{\text{Form.Sph.1 × 25::ODR.LT}}$, probing dispersion error, $P_{\text{Form.Sph.D95 \%::ODR.LT}}$, probing size error, $P_{\text{Size.Sph.1 × 25::ODR.LT}}$, and probing size error All, $P_{\text{Size.Sph.All::ODR.LT}}$. The measured values are compared to specifications provided by the manufacturer, $P_{\text{Form.Sph.1 × 25::ODR.LT,MPE}}$, $P_{\text{Form.Sph.D95 \%::ODR.LT,MPE}}$, $P_{\text{Size.Sph.1 × 25::ODR.LT,MPE}}$ and $P_{\text{Size.Sph.All::ODR.LT,MPE}}$, respectively, to determine conformity, as described in ISO 10360-8:2013, 7.1.

If multiple orientations of the ODR are permitted in normal operation, these orientations should be utilized in the measurement of the test sphere.

NOTE Orientation of the ODR refers to the roll, pitch and yaw of the ODR relative to the incoming beam from the laser tracker – these are not to be confused with the azimuth and elevation angles of the laser tracker.

G.3 Registration errors

The registration of the ODR to the main SMR probe shall follow the method of ISO 10360-9:2013. A test sphere is measured with both the ODR (as shown in Figure G.2) and the SMR. Quantities to be measured include multiple probing system form error, $P_{\text{Form.Sph.2x25::MPS.LT}}$, multiple probing system size error, $P_{\text{Size.Sph.2x25::MPS.LT}}$, and multiple probing system location value, $L_{\text{Dia.2x25::MPS.LT}}$. The measured values are compared to specifications provided by the manufacturer, $P_{\text{Form.Sph.2x25::MPS.LT,MPE}}$, $P_{\text{Size.Sph.2x25::MPS.LT,MPE}}$ and $L_{\text{Dia.2x25::MPS.LT,MPE}}$, respectively, to determine conformity, as described in ISO 10360-9:2013, 7.1.

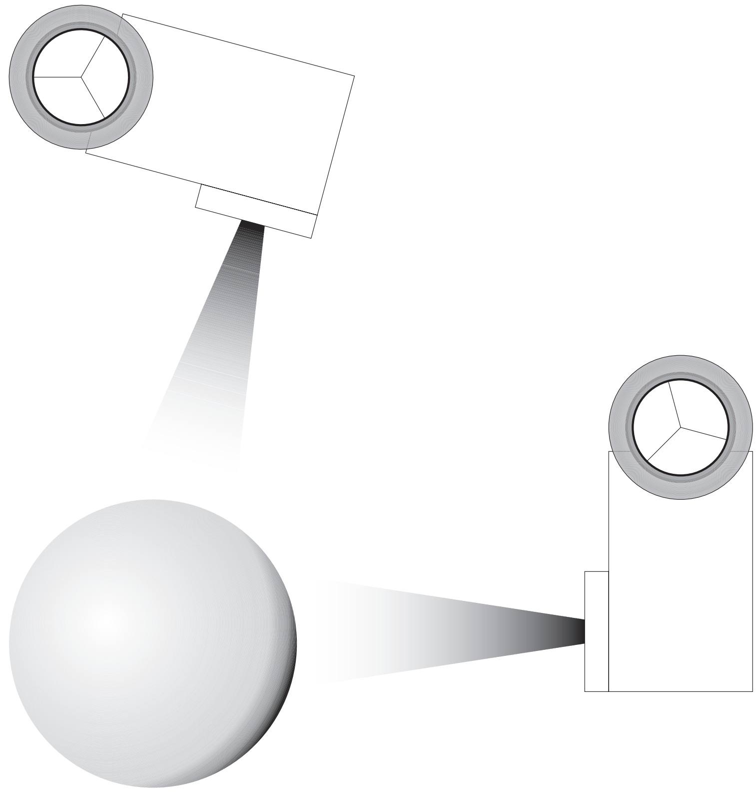


Figure G.2 — Measurement of the test sphere using the ODR

G.4 Flat form measurement

The flat form measurement is performed in any one location of the measuring volume. Measurements shall be performed according to ISO 10360-8:2013, 6.4. If desired, position (2) of the flat may be obtained by leaving the flat in position (1) and changing the orientation of the scanner. The quantity $E_{\mathrm{Form.Pla.D95\ \%:ODR}}$ is measured and compared to the $E_{\mathrm{Form.Pla.D95\ \%:ODR,MPE}}$ specifications provided by the manufacturer to determine conformity, as described in ISO 10360-8:2013, 7.1.

G.5 Symbols pertaining to this annex

Table G.1 — Quantities related to ODR tests

Symbol	Meaning
$P_{\mathrm{Form.Sph.1\times 25:ODR:LT}}$	Probing form error for ODR (25 points)
$P_{\mathrm{Form.Sph.D95\ \%:ODR:LT}}$	Probing form error for ODR (95 % of the points)
$P_{\mathrm{Size.Sph.1\times 25:ODR:LT}}$	Probing size error for ODR (25 points)
$P_{\mathrm{Size.Sph.All:ODR:LT}}$	Probing size error for ODR (all points)
$E_{\mathrm{Form.Pla.D95\ \%:ODR:LT}}$	Flat form error of measurement with ODR (95 % of the points)
$P_{\mathrm{Form.Sph.1\times 25:ODR:LT,MPE}}$	Maximum permissible error of probing form for ODR (25 points)
$P_{\mathrm{Form.Sph.D95\ \%:ODR:LT,MPE}}$	Maximum permissible error of probing form for ODR (95 % of the points)
$P_{\mathrm{Size.Sph.1\times 25:ODR:LT,MPE}}$	Maximum permissible error of probing size for ODR (25 points)
$P_{\mathrm{Size.Sph.All:ODR:LT,MPE}}$	Maximum permissible error of probing size for ODR (all points)
$E_{\mathrm{Form.Pla.D95\ \%:ODR:LT,MPE}}$	Maximum permissible error of flat form measurement with ODR (95 % of the points)
$P_{\mathrm{Form.Sph.}n\mathrm{x25::MPS.LT}}$	Multiple probing system form error

Table G.1 *(continued)*

Symbol	Meaning
$P_{\text{Size.Sph.}n\text{x25::MPS.LT}}$	Multiple probing system size error
$L_{\text{Dia.}n \times \text{25::MPS.LT}}$	Multiple probing system location error
$P_{\text{Form.Sph.}n\text{x25::MPS.LT,MPE}}$	Maximum permissible multiple probing system form error
$P_{\text{Size.Sph.}n\text{x25::MPS.LT,MPE}}$	Maximum permissible multiple probing system size error
$L_{\text{Dia.}n \times \text{25::MPS.LT,MPE}}$	Maximum permissible multiple probing system location error

Annex H
(informative)

Relation to the GPS matrix model

H.1 General

For full details about the GPS matrix model, see ISO 14638.

H.2 Information about this document and its use

This document specifies the acceptance test for verifying that the performance of a laser tracker used for measuring point-to-point distances is as stated by the manufacturer. It also specifies the reverification test that enables the user to periodically reverify the performance of a laser tracker used for measuring point-to-point distances.

H.3 Position in the GPS matrix model

This document is a general GPS standard, which influences chain link F of the chains of standards on size, distance, radius, angle, form, orientation, location and run-out in the general GPS matrix, as graphically illustrated in Table H.1.

Table H.1 — ISO GPS Standards matrix model

	Chain links						
	A	**B**	**C**	**D**	**E**	**F**	**G**
	Symbols and indications	Feature requirements	Feature properties	Comformance and non-conformance	Measurement	Measurement equipment	Calibrations
Size						•	
Distance						•	
Form						•	
Orientation						•	
Location						•	
Run-out						•	
Profile surface texture							
Areal surface texture							
Surface imperfections							

H.4 Related International Standards

The related International Standards are those of the chains of standards indicated in Table H.1.

Bibliography

[1] ISO 3650, *Geometrical Product Specifications (GPS) — Length standards — Gauge blocks*

[2] ISO 8015, *Geometrical product specifications (GPS) — Fundamentals — Concepts, principles and rules*

[3] ISO 10360-2:2009, *Geometrical product specifications (GPS) — Acceptance and reverification tests for coordinate measuring machines (CMM) — Part 2: CMMs used for measuring linear dimensions*

[4] ISO 14253-1, *Geometrical product specifications (GPS) — Inspection by measurement of workpieces and measuring equipment — Part 1: Decision rules for verifying conformity or nonconformity with specifications*

[5] ISO 14638, *Geometrical product specifications (GPS) — Matrix model*

[6] ISO 17450-1, *Geometrical product specifications (GPS) — General concepts — Part 1: Model for geometrical specification and verification*

[7] ISO/IEC Guide 98-4, *Uncertainty of measurement — Part 4: Role of measurement uncertainty in conformity assessment*

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