Acceptance Test and Reverification Test for Coordinate Measuring Machines (CMMs) — Part 2: CMMs Used for Measuring Linear Dimensions

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Acceptance Test and Reverification Test for Coordinate Measuring Machines (CMMs) —
Part 2: CMMs Used for Measuring Linear Dimensions

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This Technical Report will be revised when the Society approves the issuance of a new edition. There will be no addenda issued to this edition.

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ASME B89.4.10360.2

Acceptance test and reverification test for coordinate measuring machines (CMMs) — Part 2: CMMs used for measuring linear dimensions.

The ASME B89.4.10360.2 Technical Report is based on, and is compliant with, the final draft International Standard (FDIS) ISO 10360-2, expected to be published as an International Standard in 2009. The ISO FDIS text appears verbatim in this Technical Report. Whenever the phrase "International Standard" appears, it refers to the ISO 10360-2 FDIS document. Additional requirements and information specific to the ASME B89.4.10360.2 Technical Report are included in bordered text boxes such as this one. Normative material is a fundamental part of the ASME B89.4.10360.2 Technical Report and, if applicable, supersedes the corresponding ISO 10360-2 normative text. In particular, there are a few cases where text appearing in ISO 10360-2 is in conflict with the Normative text of ASME B89.4.10360.2, and accordingly the ASME B89.4.10360.2 requirements shall govern. The corresponding ISO text has been put into a "strikeout" (~~strikeout~~) font in those cases. Informative material in this Technical Report is meant to provide additional benefit for the reader.

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Note: Annexes E and F originally in the ISO Standard are omitted in the B89 Technical Report because they pertain only to the location of other ISO documents and are not relevant to this Report.

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 10360-2 was prepared by Technical Committee ISO/TC 213, *Dimensional and geometrical product specifications and verification*.

This third edition cancels and replaces the second edition (2001) which has been technically revised.

ISO 10360 consists of the following parts, under the general title *Geometrical Product Specifications (GPS) — Acceptance and reverification tests for coordinate measuring machines (CMM)*:

— *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 4: CMMs used in scanning measuring mode*

— *Part 5: CMMs using single and multiple stylus contacting probing systems*

— *Part 6: Estimation of errors in computing of Gaussian associated features*

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Introduction

This part of ISO 10360 is a geometrical product specification (GPS) standard and is to be regarded as a general GPS standard (see ISO/TR 14638). It influences link 5 of the chains of standards on size, distance, radius, angle, form, orientation, location, run-out and datums. ~~For more detailed information of the relation of this part of ISO 10360 to other standards and the GPS matrix model see Annex F.~~

Informative
The ASME B89.4.10360.2 Technical Report does not include the ISO GPS matrix; for information on this topic see the appropriate ISO documents for this material.

The tests of this part of ISO 10360-2 have three technical objectives,

1) to test the error of indication of a calibrated test length using a probing system without any ram axis stylus tip offset,

2) to test the error of indication of a calibrated test length using a probing system with a specified ram axis stylus tip offset, and

3) to test the repeatability of measuring a calibrated test length.

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

Clause 3 in this part of ISO 10360 contains definitions that supersede similar definitions in ISO 10360-1:2000.

The revised definitions are required to avoid an ambiguity that would otherwise have been introduced with this issue of ISO 10360-2. Also, definition 3.6 supersedes effectively an identical definition in ISO 10360-1:2000, because the symbols used have been revised and expanded for clarification.

Informative
Definitions that are specific to the ASME B89.4.10360.2 Report are included in bordered text boxes.

Informative
Within the ISO 10360-2 text, a comma is used to represent a decimal. For example, 0,5 would be the decimal form of ½.   Similarly, the ISO 10360-2 text contains spellings that are different from American English usage (e.g., artefact). These are left unchanged in this Report.

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Geometrical Product Specifications (GPS) — Acceptance and reverification tests for coordinate measuring machines (CMM) — Part 2: CMMs used for measuring linear dimensions

1 Scope

This part of ISO 10360 specifies the acceptance tests for verifying the performance of a CMM used for measuring linear dimensions as stated by the manufacturer. It also specifies the reverification tests that enable the user to periodically reverify the performance of the CMM.

The acceptance and reverification tests given in this part of ISO 10360 are applicable only to Cartesian CMMs using contacting probing systems of any type operating in the discrete-point probing mode.

This International Standard does not explicitly apply to:

— non-cartesian CMMs, however, the parties may apply this part of 10360 to non-Cartesian CMMs by mutual agreement,

— CMMs using optical probing, however, the parties may apply this approach to optical CMMs by mutual agreement.

Informative

For information on non-Cartesian CMMs, see ASME B89.4.22 regarding articulating arm CMMs and ASME B89.4.19 for laser trackers.

This International Standard specifies performance requirements that can be assigned by the manufacturer or the user of a CMM, the manner of execution of the acceptance and reverification tests to demonstrate the stated requirements, rules for proving conformance, and applications for which the acceptance and reverification tests can be used.

Informative

ASME B89.4.10360.2 provides a well defined set of specifications for a CMM manufacturer to describe their CMM performance and for users to verify the specified performance. This Report does not mandate testing (by either the manufacturer or the user) to verify CMM performance. The amount of testing, and which party will bear the cost of testing, is a business decision and must be negotiated between the two parties.

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2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the cited editions apply. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 10360-1:2000, *Geometrical Product Specifications (GPS) — Acceptance and reverification test for coordinate measuring machines (CMM) — Part 1: Vocabulary*

ISO 14253-1:1998, *Geometrical Product Specifications (GPS) — Inspection by measurement of workpieces and measuring equipment — Part 1: Decision rules for proving conformance or non-conformance with specifications*

ISO 14660-1:1999, *Geometrical Product Specifications (GPS) — Geometrical features — Part 1: General terms and definitions*

ISO/TS 23165:2006, *Geometrical product specifications (GPS) — Guidelines for the evaluation of coordinate measuring machine (CMM) test uncertainty*

International Vocabulary of Basic and General Terms in Metrology (VIM). BIPM, IFCC, IEC, ISO, IUPAC, IUPAP, OIML, 2nd edition, 1993

Normative References

ASME B89.7.3.1 - 2001 *Guidelines for Decision Rules: Considering Measurement Uncertainty in Determining Conformance to Specifications*

ASME B89.7.5 - 2006 *Metrological Traceability of Dimensional Measurements to the SI Unit of Length*

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3 Terms and definitions

For the purposes of this part of ISO 10360, the terms and definitions given in ISO 10360-1, ISO 14253-1, ISO 14660-1, ISO/TS 23165 and VIM apply.

3.1
ram axis stylus tip offset
L
distance (orthogonal to the ram axis) between the stylus tip and a reference point

NOTE 1   The reference point is defined by the manufacturer. If no manufacturer-defined reference point is known, the user chooses a reference point close to the probe system mount.

NOTE 2   The reference point is usually in or near the probe system.
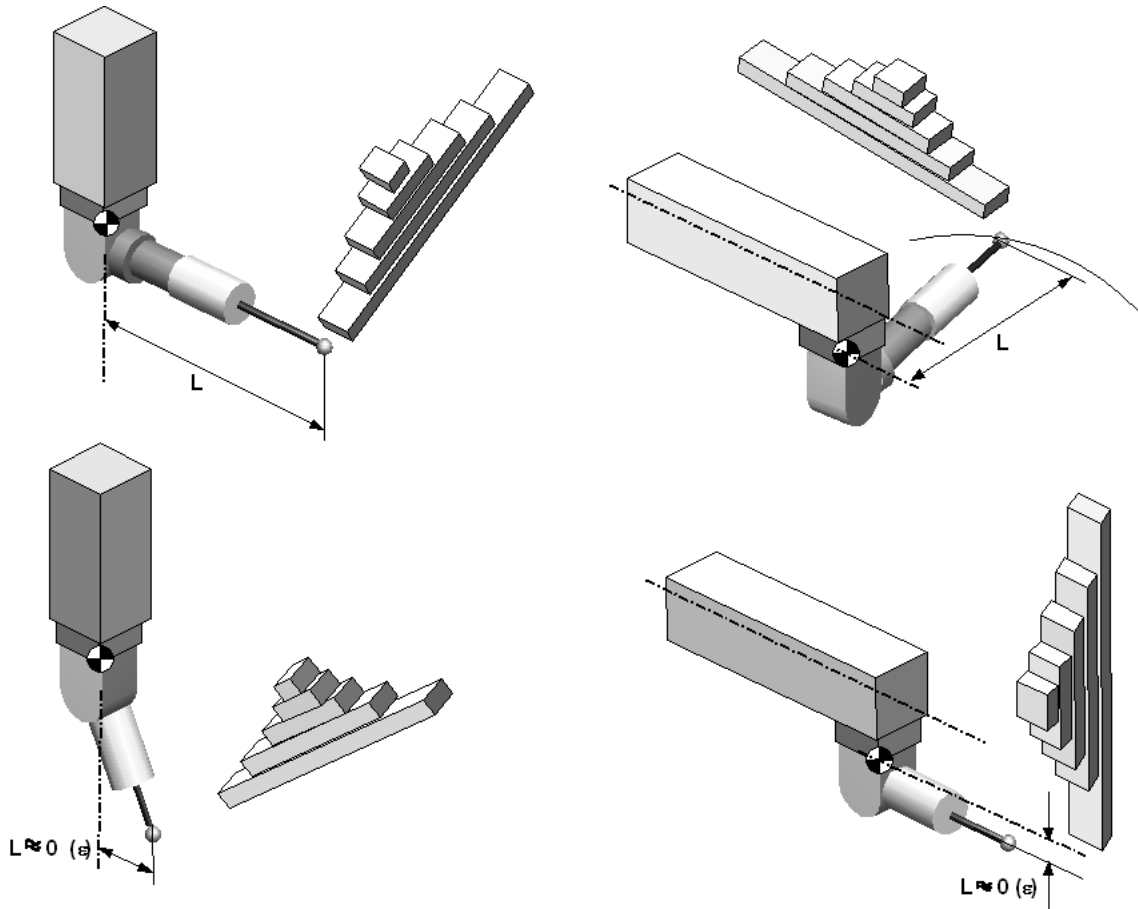
Figure 1 — Examples of the ram axis stylus tip offset for the case of an articulated probing system

3.2
coefficient of thermal expansion (CTE)
α
linear thermal expansion coefficient of a material at 20 °C

3.3
normal CTE material
material with a CTE between 8×10^{-6} /°C and 13×10^{-6} /°C

3.4
length measurement error
E_{L}
error of indication when measuring a calibrated test length using a CMM with a ram axis stylus tip offset of L, using a single probing point (or equivalent) at each end of the calibrated test length

NOTE 1   In this International Standard, L = 0 and L = 150 mm, (default values) are specified.

NOTE 2   See Annex B for the requirements of point sampling strategies.

3

3.5
repeatability range of the length measurement error
R_0
range (largest minus smallest) of three repeated length measurement errors measured by a CMM with zero ram axis stylus tip offset

3.6
maximum permissible error of length measurement
$E_{L, MPE}$
extreme value of the length measurement error, E_L, permitted by specifications

NOTE 1   In this International Standard, $L = 0$ and $L = 150$ mm, (default values) are specified.

NOTE 2   A maximum permissible error (MPE) as opposed to a maximum permissible limit (MPL) specification is used when the test measurements determine errors; hence, testing an MPE specification requires the use of calibrated artefacts.

NOTE 3   The MPE may be expressed in using any of the methods shown in Figure 12, Figure 13, and Figure 14 of ISO 10360-1:2000.

> **Informative**
> See Annex J for methods of expressing the MPE according to ISO 10360-1:2000

3.7
maximum permissible limit of the repeatability range
$R_{0, MPL}$
extreme value of the repeatability range of the length measurement error, R_0, permitted by specifications

NOTE 1   A maximum permissible limit (MPL) as opposed to a maximum permissible error (MPE) specification is used when the test measurements are not errors; hence, testing an MPL specification does not require the use of calibrated artefacts.

NOTE 2   The MPL may be expressed in using any of the methods shown in Figure 12, Figure 13, and Figure 14 of ISO 10360-1:2000.

> **Informative**
> See Annex J for methods of expressing the MPL according to ISO 10360-1:2000

3.8
dual ram CMM
CMM composed of two independent rams and a method to report the coordinate measurements from both rams in a single coordinate system

NOTE 1 The two rams usually share part of their measuring range, but this is not required.

NOTE 2 The method to establish a single coordinate system may require an alignment procedure.

NOTE 3 A dual ram CMM may report the results of each ram in separate coordinate systems; see simplex operating mode.

3.9
simplex operating mode
method of using a dual ram CMM in which the two rams are treated as separate measuring systems

NOTE In the simplex operating mode, the coordinate measurements from the two rams are not reported in a single coordinate system.

3.10
duplex operating mode
method of using a dual ram CMM in which the coordinate measurements from the two rams are reported in a single coordinate system

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Informative

3.11 X (or Y or Z) axis length measurement error, $E_{0X(\text{or Y or Z})}$
length measurement error with the calibrated test length oriented along the X (or Y or Z) axis of the CMM and passing though the center of the measuring volume

3.12 maximum permissible error of X (or Y or Z) axis length measurement, $E_{0X(\text{or Y or Z), MPE}}$
extreme value of the X (or Y or Z) axis length measurement error, $E_{0X\ (\text{or Y or Z})}$, permitted by specifications

NOTE: The specification of the length measurement error along each axis is very useful for economic considerations when selecting a CMM. For many workpieces the smallest tolerance is a linear dimension, e.g. the distance between two alignment pins on an engine block. Furthermore, this linear dimension is often oriented along a CMM axis; hence it is the axis length measurement error that is critical. Since the $E_{0X,\ MPE}$ specification is typically smaller than the $E_{0,\ MPE}$ specification, considerable expense may be saved by examination of the $E_{0X,\ MPE}$ specification.

3.13 repeatability of point coordinates, R_{Pt}
range of the center coordinates of a sphere along a CMM axis, computed from ten repeated measurements

3.14 maximum permissible limit of the repeatability of point coordinates, $R_{Pt,\ MPL}$
extreme value of the repeatability of point coordinates, R_{Pt}, for any CMM axis, as permitted by specifications

NOTE: The repeatability of point coordinates, R_{Pt}, is a recommended specification since it is simple to perform and can quickly detect CMM problems before more time intensive testing is undertaken. It also provides a reasonable estimate of the expected variation in the coordinates of a measured point.

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4 Symbols

For the purpose of this International Standard, the symbols of Table 1 apply.

Table 1 — Symbols

Symbol	Meaning
E_L	length measurement error
R_0	repeatability range of the length measurement error
$E_{L, MPE}$	maximum permissible error of length measurement
$R_{0, MPL}$	maximum permissible limit of the repeatability range

NOTE   See Clause 9 for the indications of these symbols in product documentation, drawings, data sheets etc.

Normative

4.1 Thermal parameters

Symbols for the thermal environment specifications, observations, and derating.
See Clause 5.1.1 and Clause 7.1.3 for the measurement instructions for these quantities

Symbol	Meaning
T_{S_MIN}	Minimum Temperature Specification
T_{MIN}	Minimum Observed Temperature
T_{S_MAX}	Maximum Temperature Specification
T_{MAX}	Maximum Observed Temperature
T_{AVG}	Average Observed Temperature in Envelope
ΔT_{S_1}	Maximum Change in Temperature per Hour Specification
ΔT_1	Maximum Observed Change in Temperature in One Hour
ΔT_{S_24}	Maximum Change in Temperature per Day Specification
ΔT_{24}	Maximum Observed Change in Temperature in 24 Hours
ΔT_{S_H}	Maximum Change in Temperature per Meter Horizontally Specification
ΔT_H	Observed Change in Temperature per Meter Horizontally
ΔT_{S_V}	Maximum Change in Temperature per Meter Vertically Specification
ΔT_V	Observed Change in Temperature per Meter Vertically
ΔL_{NDE}	Nominal Differential Expansion Length used in Derating
ΔL_{UNDE}	Uncertainty in Nominal Differential Expansion Length used in Derating
ΔL_T	Thermal Variation Length used in Derating
ΔL_{TVE}	Thermal Variation Error used in Derating
f_{NDE}	Thermal fraction associated with NDE used for derating
$f_{\Delta T\_1}$	Thermal fraction associated with hourly thermal variation used for derating
$f_{\Delta T\_24}$	Thermal fraction associated with daily thermal variation used for derating
f_{TVE}	Thermal fraction associated with TVE used for derating
$\Delta E_{UL, MPE}$	Change Permitted by Derating in the Upper Limit of an MPE
$\Delta E_{LL, MPE}$	Change Permitted by Derating in the Lower Limit of an MPE

5 Environmental and metrological requirements

5.1 Environmental conditions

Limits for permissible environmental conditions such as temperature conditions, air humidity and vibration at the site of installation 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 10360-2 testing will be performed within the specified limits (as supplied in the data sheet of the manufacturer. ~~See ISO 10360-1, Amendment 1~~).

> **Informative**
>
> See Annex I for the data sheet.

The user is responsible for providing the environment enclosing the CMM as specified by the manufacturer in the data sheet.

~~If the environment does not meet the specifications then the maximum permissible errors, $E_{0, MPE}$, $E_{L, MPE}$, and maximum permissible limit $R_{0, MPL}$ cannot be required to be verified.~~

> **Normative**
>
> The manufacturer's specifications for environmental conditions are stated in Annex I of this Report.
>
> The ASME B89.4.10360.2 Technical Report provides a means to verify performance when the environment does not meet the manufacturer's specifications; see 5.1.1 and 7.1.3.

Normative

5.1.1 Thermal environment specification and measurement

If the environment does not meet the manufacturer's thermal specifications then a thermal derating o the specifications will be performed in accordance with clause 7.1.3.

The temperature specifications in the data sheet from Annex I are shown below:

Ambient Temperature:

From T_{S_MIN} =___ °C to T_{S_MAX} =___ °C

Maximum temperature gradients

Time: ΔT_{S_1} = ___ °C per hour

ΔT_{S_24} = ___ °C per day

Space: ΔT_{S_V} = ___ °C per meter vertical

ΔT_{S_H} = ___°C per meter horizontal

Effective CTE for CMM Scales: ____μm per m per °C (required only for CMMs without therma compensation capability).

In this Report the temperature specifications have the following meaning. The ambient temperature specifications apply to the envelope of the CMM; this is the volume of space occupied by the entire CMM structure under the full extent of travel of all axes, starting 25 mm (one inch) above the floor The specifications apply to the room with the CMM present and under normal power requirements hence attention should be paid to the power dissipation of the CMM and the thermal environmen provided accordingly.

The specifications of the minimum, T_{S_MIN}, and maximum, T_{S_MAX}, ambient temperature appl throughout the envelope of the CMM. Hence the observed ambient temperature, which includes th effects of all spatial gradients, must be contained within these temperature limits.

The temperature sensors shall have a time constant of approximately five minutes. (This is sufficientl slow to avoid spurious readings, e.g. when a person walks past a sensor, but sufficiently fast to dete changes that can affect small CMM components, e.g. styli shafts.) This can be achieved by affixin the sensor to a piece of metal with a mass of approximately a US quarter dollar, e.g. taping the senso to the quarter and providing a good thermal contact between the sensor and the coin. Alternatively, a five minute moving average may be used, providing the sensor is sampled at 30 second (or shorter intervals. The five minute time constant is then produced by an average of the all the temperature data within a five-minute interval.

The specified hourly variation, ΔT_{S_1}, is the absolute value of the maximum difference between an two measurements separated in time by one hour or less. The specified daily variation, ΔT_{S_24}, is th absolute value of the maximum difference between any two measurements separated in time by 2 hours or less.

The specified horizontal and vertical gradients, ΔT_{S_H} and ΔT_{S_V}, are the maximum of the absolut value of the difference between paired sensors divided by the distance between the sensors (i meters). Measurements of spatial gradients shall be based on the simultaneous readings of tw sensors separated by no less than the lesser of: one meter or 50 % of the CMM envelope in tha spatial direction.

The expanded (k=2) uncertainty of the temperature measurement shall be no greater than the less of 0.5 °C or 25 % of the range ($T_{S\_MAX} - T_{S\_MIN}$).

NOTE   In measuring the temperature, attention should be given to thermal effects from radiative heat transfer t the CMM, as temperature sensors in the air may not detect this adequately, or may report higher temperature values than the CMM surface, depending on placement. Direct sunlight falling on the machine is usually a sourc of such error, and other nearby "hot spots" may also contribute problematic infrared radiation.

5.2   Operating conditions

The CMM 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 are, for example:

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

b)   stylus system configuration,

c)   cleaning procedures for stylus tip,

d)   probing system qualification,

e)   thermal stability of the probing system before calibration,

f)   weight of stylus system and/or probing system,

g)   location, type, number of thermal sensors.

5.3   Length measurement error, E_L

The length measurement errors, the E_L values, shall not exceed the maximum permissible error,

$E_{L, MPE}$ stated by:

⸺   the manufacturer, in the case of acceptance tests,

⸺   the user, in the case of reverification tests.

The length measurement errors (the E_L values) and the maximum permissible error of length measurement, $E_{L, MPE}$, are expressed in micrometers.

NOTE   The default values of L are 0 and 150 mm, hence, $E_L = E_0$ and $E_L = E_{150}$

Informative

5.3.1 X (or Y or Z) axis length measurement error, $E_{0X (or Y or Z)}$

The X (or Y or Z) axis length measurement errors, the $E_{0X (or Y or Z)}$ values, shall not exceed the maximum permissible error, $E_{0X (or Y or Z),MPE}$, as stated by:

⸺   the manufacturer, in the case of acceptance tests;

⸺   the user, in the case of reverification tests.

The X (or Y or Z) axis length measurement errors, (the $E_{0X (or Y or Z)}$ values) and the maximum permissible errors, $E_{0X (or Y or Z), MPE}$, are expressed in micrometers.

5.4   Repeatability range of the length measurement error, R_0

The repeatability range of the length measurement errors, the R_0 values, shall not exceed the maximum permissible limit, $R_{0, MPL}$, as stated by:

—   the manufacturer, in the case of acceptance tests;

—   the user, in the case of reverification tests.

The repeatability range of the length measurement error, (the R_0 values), and the maximum permissible limit of the repeatability range, $R_{0,\,MPL}$, are expressed in micrometers.

Informative
5.4.1 Repeatability of point coordinates, R_{Pt}

The repeatability of point coordinates, the R_{Pt} values, shall not exceed the maximum permissible limit, $R_{Pt,\,MPL}$, as stated by:

—   the manufacturer, in the case of acceptance tests;

—   the user, in the case of reverification tests.

The repeatability of point coordinates, (the R_{Pt} values), and the maximum permissible limit of the repeatability of point coordinates, $R_{Pt,\,MPL}$, are expressed in micrometers.

5.5   Workpiece loading effects

The length measurement error with $L = 0$ (or minimal required for clearance), E_0, shall not exceed the maximum permissible error, $E_{0,\,MPE}$, as stated by the manufacturer when the CMM is loaded with up to the maximum workpiece mass for which the CMM performance is rated. Testing of the length measurement error, E_0, may be conducted under any workpiece load (from zero up to the rated maximum workpiece load), selected by the user subject to the following conditions:

—   The physical volume of the load supplied for testing must lie within the measuring volume of the CMM and the load must be free-standing;

—   The manufacturer may specify a limit on the maximum load per unit area (kg/m^2) on the CMM support (i.e., table) surface and/or on individual point loads (kg/cm^2). For point loads, the load at any specific contact point shall be no greater than twice the load of any other contact point;

—   Unless otherwise specified by the manufacturer, the load shall be approximately centrally and approximately symmetrically located at the center of the CMM table.

NOTE 1   The user and manufacturer should arrange for the availability of the load.

NOTE 2   The user and the manufacturer should discuss the loading of the CMM table since access to measurement positions may be impaired by the load.

6   Acceptance tests and reverification tests

6.1   General

Acceptance tests are executed according to the manufacturer's specifications and procedures that are in compliance with this International Standard. In particular, unless the user supplies the calibrated test length ~~(subject to the restrictions of ISO/TS 23165)~~ the manufacturer may choose the

artefact representing the calibrated test length from those described in Annex B and Annex D.

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

Issues associated with dual ram CMMs are discussed in 6.6.

NOTE   This International Standard does not explicitly apply to CMMs using optical probing, however if by mutual agreement the parties apply this approach to optical CMMs then additional issues, such as the following, need to be considered:

—   In the case of two dimensional sensors (no ram movement) an index 2D may be used for indication, e.g. $E_{0\text{-}2D;}$

—   In case of two dimensional systems the number and location of the measurement positions may be reduced;

—   Specifications for the magnification and illumination;

—   Artefact issues such as material and surface finish affect the test results;

—   Bi-directional probing may or may not be possible depending on the artefact and probing system (see Annex B).

Normative

If the user supplies the calibrated test length, the test uncertainty (see Annex E) at the time and conditions of testing must be no greater than that stated by the manufacturer.

Informative

6.1.1 Measurement procedure for the repeatability of point coordinates, R_{Pt}

The repeatability of point coordinates test should be performed first, in order to quickly determine if there are significant problems with the CMM prior to the more extensive tests of clauses 6.3, 6.4, and 6.5

Mount a test sphere with a nominal diameter of no less than 10 mm and no greater than 50 mm in approximately the center of the CMM table. (The test sphere used in ASME B89.4.10360.5 may be used for this procedure.) Measure the test sphere with four (and no more than four) probing points. The default pattern has three points spaced at 120 degrees around the "equator" of the sphere and one point at the "pole." Record the coordinates of the test sphere, e.g., the X, Y, and Z coordinates of the sphere center, where X, Y, and Z are the CMM axis directions. Repeat the test sphere measurement using this procedure a total of 10 times.

6.2 Principle

The principle of the assessment method is to use a calibrated test length, traceable to the meter, to establish whether the CMM is capable of measuring within the stated maximum permissible error of length measurement for a CMM with a specified ram axis stylus tip offset (both 0 and 150), $E_{0,\text{MPE}}$ and $E_{150,\text{MPE}}$, and within the stated maximum permissible limit for the repeatability range, $R_{0,\text{MPL}}$.

The assessment shall be performed by comparison of the indicated values of five different calibrated test lengths, each measured three times, relative to their calibrated values. The indicated values are calculated by point-to-point length measurements projected onto the alignment direction (see also Annex C).

Each of the three repeated measurements is to be arranged in the following manner: if one end of the calibrated test length is labeled "A" and the other end "B" then the measurement sequence is either $A_1 B_1, A_2 B_2, A_3 B_3$ or $A_1 B_1, B_2 A_2, A_3 B_3$. Other sequences such as $A_1 A_2 A_3$, $B_1 B_2 B_3$ are not permitted. Each of the three repeated measurements shall have its own unique measured points. That is, in general, B_1, B_2 and B_3 must be different actual points of the same target point B. Once the measurement sequence for a test length has begun no additional probing points shall be measured other than those required to measure its length; e.g., no alignment points are permitted between the measurement of A_1 and B_3.

For CMMs without workpiece thermal expansion compensation, the uncorrected differential thermal expansion between the CMM and the calibrated test length can produce a significant error, hence this International Standard also requires the disclosure of the test length CTE. For CMMs with workpiece thermal expansion compensation this thermally induced error is greatly reduced. For these CMMs a significant portion of the residual thermal error is due to the uncertainty in the test length's CTE (i.e. resulting in imperfect thermal expansion correction), hence this International Standard requires the disclosure of the uncertainty in the CTE of the test length.

6.3 Length measurement error with zero ram axis stylus tip offset, E_0

6.3.1 General

The E_0 test shall be conducted using a ram axis stylus tip offset of zero or as small as practical. It is recognized that depending on the CMM type, the artefact used as a calibrated test length, and the particular measurement line, a nonzero ram axis stylus tip offset may be required in order to access the gauging points of the calibrated test length. For these measurement situations, the smallest ram axis stylus tip offset practical shall be used.

NOTE 1   See Figure 1 for examples of ram axis stylus tip offsets, including some small, nonzero offsets.

NOTE 2   Prior to beginning the extensive testing described in the following sections, it is recommended to perform the single or multiple stylus probing system test, as appropriate, described in ISO10360-5, to quickly ensure that the probing system is operating within specifications (see also Annex E).

6.3.2 Measuring equipment

The longest calibrated test length for each position shall be at least 66 % of the maximum travel of the CMM along a measurement line through the calibrated test length. Hence the minimum allowable longest calibrated test length positioned along a body diagonal will be longer than the minimum allowable longest calibrated test length positioned along an axis direction. Each calibrated test length shall differ significantly from the others in length. Their lengths shall be well distributed over the measurement line. In general, the five calibrated test lengths used in one position may differ in their lengths from those used in another position, for example due to the extent of CMM travel along different measurement lines.

NOTE   An example of well distributed calibrated test lengths over a one meter measurement line is: 100 mm, 200 mm, 400 mm, 600 mm, 800 mm.

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 the case that the calibrated test length is composed of a uni-directional length and a short gauge block (see Annex B), the CTE shall be considered to be that of the uni-directional length. The default for a calibrated test length is a normal CTE material unless the manufacturer's specifications explicitly state otherwise.

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

EXAMPLE

$E_{0,\ MPE}$*
* artefact is super-invar with a CTE no greater than 0.5×10^{-6} /°C and with a CTE expanded uncertainty (k = 2) no greater than 0.3×10^{-6} /°C

For the case where the manufacturer's specification states that the calibrated test lengths will be a non-normal CTE material AND the CTE is less than 2×10^{-6} /°C, then an additional measurement will be performed as described in 6.3.3.3.

A low CTE test length can be mathematically adjusted to give the apparent behavior of a normal CTE material test length subject to the requirements of Annex D, however, this calibrated test length is still considered to have a low CTE and is subject to the requirement of 6.3.3.3.

See Annex B for examples of a calibrated test length.

6.3.3   Procedure

6.3.3.1   Measurement positions

Five different calibrated test lengths shall be placed in each of seven different positions (locations and orientations) in the measuring volume of the CMM, and each length shall be measured three times, for a total of 105 measurements. Four of the seven positions shall be the space diagonals, as shown in the table below. The user may specify the remaining three positions; the default positions are parallel to each of the CMM axes, as shown in Table 2.

Table 2 — Orientation in the measuring volume

Position number	Orientation in the measuring volume	Required or default
1	Along the diagonal in space from point (1, 0, 0) to (0, 1, 1)	Required
2	Along the diagonal in space from point (1, 1, 0) to (0, 0, 1)	Required
3	Along the diagonal in space from point (0, 1, 0) to (1, 0, 1)	Required
4	Along the diagonal in space from point (0, 0, 0) to (1, 1, 1)	Required
5	Parallel to the machine scales from point (0, ½, ½) to (1, ½, ½)	Default
6	Parallel to the machine scales from point (½, 0, ½) to (½, 1, ½)	Default
7	Parallel to the machine scales from point (½, ½, 0) to (½, ½, 1)	Default
NOTE For specifications in this table, opposite corners of the measuring volume are assumed to be (0, 0, 0) and (1, 1, 1) in coordinates (X, Y, Z).		

NOTE 1   The manufacturer may, at their discretion, specify the maximum permissible error of length measurement with zero ram axis stylus tip offset, for each CMM axis, i.e. positions 5-6-7.

The notation shall be: E_{0X} and $E_{0X, MPE}$, E_{0Y} and $E_{0Y, MPE}$, and E_{0Z} and $E_{0Z, MPE}$.

Informative

See clause 6.3.4.1 for the details of determining the length measurement error for each axis.

NOTE 2   For CMMs with a high aspect ratio between the length of the axes, the manufacturer and the user, upon mutual agreement, are recommended to add two additional measurement positions. A high aspect ratio CMM occurs when the length of the longest axis is at least three times the length of the intermediate axis. The recommended positions, each consisting of five calibrated test lengths, each measured three times, are the two (corner-to-corner) diagonals in a plane perpendicular to the longest axis, i.e., if X is the longest axis, then the two diagonals are in the Y-Z plane and located approximately at the midpoint of the X axis.

6.3.3.2   Measurement procedure

Set up and qualify the probing system in accordance with the manufacturer's normal procedures (see 5.2). All probing system qualifications shall be performed using the manufacturer supplied reference sphere (or other artefact supplied by the manufacturer for probe qualifications in the normal use of the CMM) and shall not make use of any test artefact or other artefacts. The ram axis stylus tip offset should be zero (or the minimal to allow clearance) to measure the calibrated test length.

For each of the five calibrated test lengths obtain three measurement results; see Annex B for details regarding the measurement procedure for specific types of test lengths. Repeat for all seven measurement positions for a total of 105 measurement results from the calibrated test lengths.

Supplementary measurements may be required for artefact alignment purposes. It is recommended that the alignment method used be consistent with the procedures used for the artefact calibration.

NOTE 1   The manufacturer should clearly specify on the data sheet the stylus system that will be used for the E_0 test; for example, a straight 20 mm long stylus shall be used in the test. If the manufacturer does not specify the stylus system the user is free to choose the system from any stylus components supplied with the CMM.

NOTE 2   Changing the stylus system may significantly change the E_0 test results.

6.3.3.3   Low CTE case

For the case where the manufacturer's specification for $E_{0, MPE}$ requires $\alpha < 2 \times 10^{-6}$ /°C (thus being a non-normal CTE), then an additional measurement will be performed on a normal CTE material calibrated test length. The normal CTE material test length shall be greater than the lesser of: 0,5 meters, OR, 50 % of the longest CMM axis travel. This measurement will be performed in the center of the CMM measuring volume and parallel to one of the CMM axes. The measurement shall be repeated three times. The manufacturer may calibrate the CTE of this test length.

NOTE 1   When a laser interferometer is used to produce the calibrated test lengths, as described in Annex B, the laser interferometer is considered a low CTE material and hence requires the measurement of a normal CTE calibrated test length.

NOTE 2   In the case of using a laser interferometer, it is good practice to measure the normal CTE artefact along a measurement line that was previously measured using the laser interferometer. The consistency of the errors of indication from the laser interferometer and from the normal CTE artefact serves as a quick check to see if the compensation for the workpiece CTE and the compensation for the index of refraction have been correctly implemented.

6.3.4   Derivation of test results

For all 105 measurements, and (if required) the three additional measurements of 6.3.3.3, calculate each length measurement error, E_0, by calculating the difference between the indicated value and the calibrated value of each test length (where the calibrated value is taken as the conventional true value of the length). The indicated value of a particular measurement of a calibrated test length may be corrected by the CMM to account for systematic errors, or thermally induced errors (including thermal expansion) if the CMM has accessory devices for these purposes. 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 5.1.

NOTE   For some CMMs, the thermal correction system requires the user to input values of the artefact's CTE and temperature as part of its automatic thermal compensation system as described in its operating documentation. This is permitted provided it is the CMM software that performs the thermal compensation. Manual thermal compensation by the user is not permitted.

Plot all length measurement errors (values of E_0) on a diagram, as indicated on the figure (Figure 12, Figure 13 or Figure 14 of ISO 10360-1:2000) that matches the expressed form of $E_{0, \text{MPE}}$.

Informative

See Annex J of this Report for Figures 12, 13 and 14 from ISO 10360-1:2000.

Informative
6.3.4.1 Axis length measurement error
Using the 15 length measurements (five lengths each repeated three times) obtained along the X axis of the CMM in clause 6.3.3, calculate each X axis length measurement error, E_{0X}, by evaluating the difference between the indicated value and the true value of each calibrated test length. The true value of the calibrated test length is taken as its calibrated value. The indicated value of a particular measurement of a calibrated test length may be corrected to account for systematic errors, or thermally induced errors (including thermal expansion) if the CMM has accessory devices for these purposes. 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 clause 5.1.

Plot all X axis length measurement errors (values of E_{0X}) on a diagram, as indicated on the figure (Figure 12, 13 or 14 of Annex J) that matches the expressed form of $E_{0X, \text{MPE}}$.

Repeat this procedure for the Y axis length errors (values of E_{0Y}) and the Z axis length errors (values of E_{0Z}).

6.4 Repeatability range of the length measurement error, R_0

For each set of three repeated measurements in 6.3, calculate the repeatability range, R_0, by evaluating the range of the three repeated length measurements.

Plot all the repeatability range values (the R_0 values) on a diagram, as indicated on the figure (Figure 12, Figure 13 or Figure 14 of ISO 10360-1:2000) that matches the expressed form of $R_{0, MPL}$.

Informative

See Annex J of this Report for Figures 12, 13 and 14 from ISO 10360-1:2000.

6.5 Length measurement error with ram axis stylus tip offset of length 150 mm, E_{150}

6.5.1 Measuring equipment

The longest calibrated test length for each position shall be at least 66 % of the maximum travel of the CMM along a line through the calibrated test length.

Each calibrated test length shall differ significantly from the others in length. Their lengths shall be well distributed over the measurement line. In general, the five calibrated test lengths used in one position may differ in their lengths from those used in another position, for example due to the extent of CMM travel along different measurement lines.

NOTE   An example of well distributed calibrated test lengths over a one meter measurement line is: 100 mm, 200 mm, 400 mm, 600 mm, 800 mm.

The default for the calibrated test length is a normal CTE material unless the manufacturer's specifications explicitly state otherwise. The manufacturer shall state the upper, and optionally lower, limit 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.

If the calibrated test length is not a normal CTE material then the corresponding $E_{150, MPE}$ values are designated with an asterisk * and an explanatory note shall be provided describing the CTE of the calibrated test length:

EXAMPLE

$E_{150, MPE}$*
* artefact is super-invar with a CTE no greater than $0,5 \times 10^{-6}$ /°C and with a CTE expanded uncertainty (k = 2) no greater than $0,3 \times 10^{-6}$ /°C
See Annex B for examples of a calibrated test length.

6.5.2 Procedure

6.5.2.1 Probe orientations

Set up and qualify the probing system in accordance with the manufacturer's normal procedures (see 5.2). All probing system qualifications shall be performed using the manufacturer supplied reference

sphere (or other artefact supplied by the manufacturer for probe qualifications in the normal use of the CMM) and shall not make use of any test artefact or other artefacts.

The default value for the ram axis stylus tip offset is 150 mm ($\pm$ 15 mm); E_{150}.

The direction of the ram axis stylus tip offset is to be oriented perpendicular to the measurement line defined by the calibrated test length and pointing along a CMM axis direction.

For each measurement the user may specify the direction of the ram axis stylus tip offset to be either pointing in the positive *or* in the negative axis direction, i.e. in either the +X or – X direction for positions 1A or 1B, and in either the +Y or –Y direction for positions 2A or 2B; see Figure 2. Hence, of the eight possible combinations of test length positions and probe orientations, the user may choose any two for testing.

6.5.2.2   Possible measurement positions and probe orientations

Unless otherwise specified (see 6.5.2.3 NOTE 3) only two of the eight possible combinations of calibrated test length positions and probe orientations are to be tested.

The user may specify either one or two calibrated test length positions from the four positions shown in Table 2.

The user may specify one or two of the probe orientations described in 6.5.2.1.

In the case where only one test length position is specified then the probe orientations shall be diametrically opposite as described in 6.5.2.1; see 6.5.2.3 NOTE 4.

If the ram axis of the CMM is designated other than the Z axis then corresponding changes shall be made to the positions and probe orientations in Table 3.

Table 3 — Orientation in the measuring volume

Position number	Orientation in the measuring volume
1A	Along the YZ plane diagonal from point (½, 0, 0) to (½, 1, 1)
1B	Along the YZ plane diagonal from point (½, 0, 1) to (½, 1, 0)
2A	Along the XZ plane diagonal from point (0, ½, 0) to (1, ½, 1)
2B	Along the XZ plane diagonal from point (0, ½, 1) to (1, ½, 0)
NOTE For specifications in this table, opposite corners of the measuring volume are assumed to be (0, 0, 0) and (1, 1, 1) in coordinates (X, Y, Z).	

NOTE   For very small CMMs, it may be necessary to translate the calibrated test length, keeping it oriented along an XZ or YZ diagonal, in order to provide sufficient clearance for measurement, e.g. Position 1A could be from point (1, 0, 0) to (1, 1, 1).

Informative

6.5.2.2.1 Recommended measurement positions
For purposes of economizing on time and money only two of the eight possible combinations are required to be tested in ISO 10360-2. It is strongly recommended that the customer negotiate with the CMM manufacturer to test additional positions, ideally all eight positions. This may involve an additional fee to compensate the manufacturer for the additional testing time; see Clause 1.

6.5.2.3 Measurements

For each combination of test length position and probe orientation, five different calibrated test lengths shall be measured three times each. Hence, for the two selected combinations a total of 30 measurements shall be performed. See Annex B for details regarding the measurement procedure for specific types of test lengths. Supplementary measurements may be required for artefact alignment purposes. It is recommended that the alignment method used be consistent with the procedures used for the artefact calibration; see Annex C.

NOTE 1   Manufacturers may specify values of $E_{L, MPE}$ for other ram axis stylus tip offset values, L, particularly for large CMMs where large stylus tip offsets are frequently used. Users with specific measurement needs may, by agreement with the manufacturer, obtain specifications of $E_{L, MPE}$ for specific values of L.

NOTE 2   For purposes of specification, the stylus tip offset default value is 150 mm ($\pm$ 15 mm); however for demonstrating conformance to specifications the manufacturer may, at their discretion, use a longer stylus if it is convenient to do so.

NOTE 3   Although only two of the eight possible combinations of test length positions and probe orientations are tested, additional testing may be performed with mutual agreement between the manufacturer and the user.

NOTE 4   It is often advantageous to select a single position and perform the test with both (diametrically opposite) probe orientations for the E_{150} test. The difference between the two errors of indication (measured with diametrically opposite probe orientations) is a measure of the effective angular rotation associated with the use of a probe with a ram axis stylus tip offset of 150 mm in that position.

NOTE 5   The position of the stylus tip, in the direction along the ram axis, should also be significantly different from that used for the E_0 test. The difference in position along the ram axis should preferably be the same, if allowed by the CMM travel, as the ram axis stylus tip offset, and may be in either direction (+ or -) along the ram axis. See 3.1 and Figure 1 showing different ram axis stylus tip offsets resulting in significantly different stylus tip locations along the ram axis.
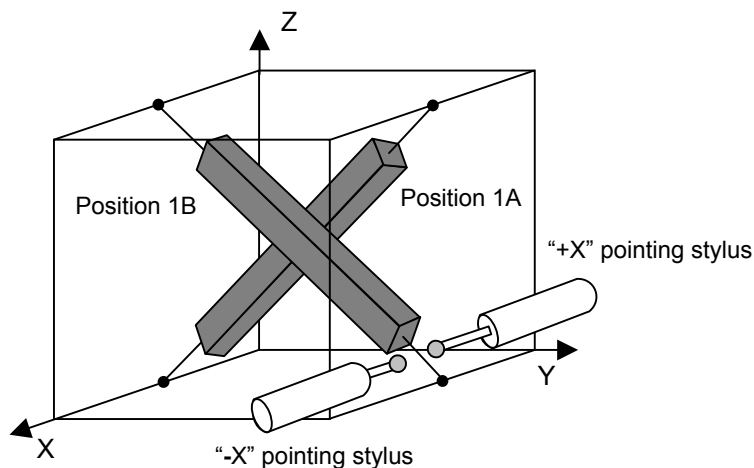

Figure 2 — Example showing two of the four possible calibrated test length positions, and two of the four possible probe orientations for the E_{150} test procedure

6.5.3   Derivation of test results

For all 30 measurements, calculate each length measurement error, E_{150}, by calculating the difference between the indicated value and the calibrated value of each test length (where the calibrated value is taken as the conventional true value of the length). The indicated value of a calibrated test length may be corrected to account for systematic errors, or thermally induced errors (including thermal expansion) if the CMM 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 5.1.

NOTE   For some CMMs, the thermal correction system requires the user to input values of the artefact's CTE and temperature as part of its automatic thermal compensation system as described in its operating documentation. This is permitted provided it is the CMM software that performs the thermal compensation. Manual thermal compensation by the user is not permitted.

Plot all the length measurement errors (values of E_{150}) on a diagram, as indicated on the figure (Figure 12, Figure 13 or Figure 14 of ISO 10360-1:2000) that matches the expressed form of $E_{150, \text{MPE}}$.

Informative

See Annex J of this Report for Figures 12, 13 and 14 from ISO 10360-1:2000.

6.6   Dual ram CMMs

6.6.1   Simplex operating mode

The performance of the individual ram machines shall be specified for the simplex operating mode. The simplex operating mode is specified by the procedures in 6.3, 6.4, and 6.5 similar to a single ram CMM. The measuring volume of a single ram used in the simplex mode is defined by the volume accessible by the individual ram using minimal probe and stylus extensions.

6.6.2   Duplex operating mode

A CMM used in duplex operating mode shall follow the procedures in 6.3, 6.4, and 6.5 with the following modifications.

NOTE 1   Before beginning the testing procedure, it is good practice to place a test sphere near the center of the measuring volume and measure the location of the sphere with each ram. The distance between the two sphere center locations should be less than $E_{0, \text{MPE}}$ for a zero length artefact; this quickly ensures that the two rams are properly qualified.

One end of each calibrated test length shall be measured with probing from one ram and the opposite end of that calibrated test length shall be measured with probing from the other ram.

It is recommended that the mid-point of each calibrated test length be located away from the center plane between the two rams.

NOTE 2   Some errors of the individual rams are nearly equal when their distances from the center plane are symmetrical. This can lead to cancellation of the effect of these errors when measuring lengths in the duplex operating mode if the two ends of the calibrated test length are located equal distances from the center plane. Displacing the calibrated test lengths' midpoints away from the center plane reduces the tendency of these symmetric errors to cancel each other. For example, when using a laser interferometer, this may easily be done by extending both rams approximately to the center of the measuring volume and then by alternating retracting

movements of one arm by one-third of its travel with retracting movements of the other arm by one-half of that arm's travel to achieve the five required test lengths spanning at least 66 % of maximum travel.

If a laser interferometer is used to produce calibrated test lengths without contact probing (analogous to B.3.3.4) then the retroreflector shall be attached to one ram and the interferometer attached to the other ram, with the laser beam determining the measurement line. Each ram shall be moved to the ends of the required five calibrated test lengths for that measurement line. To satisfy the requirements of Annex B.3 and to verify the metrological link between the two rams, each arm shall measure one point on the end of the short gauge block, repeated three times, for each measurement line.

A laser interferometer is considered a low CTE material (see Annex B) and is subject to 6.3.3.3.

To avoid ambiguity, specifications of the MPE and MPL values of dual ram CMMs shall be clearly stated as either "simplex operating mode" or "duplex operating mode".

7 Compliance with specifications

7.1 Acceptance test

Informative

The acceptance criteria of 7.1.1 are required, considering:

> if permitted, the modification of data as described in 7.1.2 and,

> if the thermal environment violates the rated conditions and at the discretion of the manufacturer, the derating of specifications as described in 7.1.3.

7.1.1 Acceptance criteria

The performance of the CMM used for measuring linear dimensions is verified if:

— the length measurement errors measured with zero ram axis stylus tip offset (values of E_0), are within the maximum permissible error of length measurement, $E_{0,\ MPE}$, as specified by the manufacturer when plotted on the appropriate diagram, as indicated on Figures 12, 13 or 14 of ISO 10360-1:2000, ~~and taking into account the uncertainty according to ISO 14253-1 and ISO/TS 23165,~~

and

— the repeatability range of the length measurement error (the R_0 values), are within the maximum permissible limit of the repeatability range, $R_{0,\ MPL}$, as specified by the manufacturer when plotted on the appropriate diagram as indicated on Figure 12, Figure 13 or Figure 14 of ISO 10360-1:2000, ~~and taking into account the uncertainty according to ISO 14253-1 and ISO/TS 23165,~~

and

— the length measurement error measured with ram axis stylus tip offset 150 mm (the E_{150} values), are within the maximum permissible error of length measurement, $E_{150,\ MPE}$, as specified by the manufacturer when plotted on the appropriate diagram, as indicated on Figure 12, Figure 13 or Figure 14 of ISO 10360-1:2000~~, and taking into account the uncertainty according to ISO 14253-1 and ISO/TS 23165~~.

For CMMs that are not intended for use with a ram axis stylus tip offset or CMMs not capable of being used with a ram axis stylus tip offset of any length L, then the verification of the length measurement error E_L, is not required.

Normative

The ISO 14253-1 decision rule cited in clause 7.1.1 is replaced by the ASME B89.7.3.1 decision rule described in Annex G. Hence, the measurement uncertainty must be taken into account according to the manner described in Annex G.

Informative

Additionally, if optional tests are specified then:

– The axis length measurement error, the $E_{0X \text{ (or Y or Z)}}$ values, are within the maximum permissible error, $E_{0X \text{ (or Y or Z), MPE}}$, as specified by the manufacturer when plotted on the appropriate diagram, as indicated on Figure 12, 13 or 14 of shown in Annex J, and taking into account the uncertainty according to Annex G

– The repeatability of point coordinates, the R_{Pt} values, shall not exceed the maximum permissible limit, $R_{Pt, MPL}$, as stated by the manufacturer when plotted on the appropriate diagram, as indicated on Figure 12, 13 or 14 shown in Annex J, and taking into account the uncertainty according to Annex G

7.1.2 Data rejection and repeated measurements

7.1.2.1 Length measurement error with zero ram axis stylus tip offset, E_0

A maximum of five of the 35 sets (or 36 sets if 6.3.3.3 is required) of three repeated measurements in accordance with clause 6.3 may have one (and no more than one) of the three values of the length measurement error outside the conformance zone.

Each such measurement that is outside the conformance zone (according to ISO 14253-1) shall be remeasured three times at the relevant position.

If all the values of the errors of indication of a calibrated test length with zero ram axis stylus tip offset from the three repeated measurements are within the conformance zone (see ISO 14253-1), then the performance of the CMM is verified at that position.

7.1.2.2 Repeatability range of the length measurement error, R_0

If a calibrated test length is remeasured according to 7.1.2.1, then the range of the three repeated measurements shall be used to determine R_0 at that position, and the three original measurements shall be discarded.

No additional repeated measurements (beyond that allowed by 7.1.2.1) shall be performed.

7.1.2.3 Length measurement error with ram axis stylus tip offset of length 150 mm, E_{150}

A maximum of two of the 10 sets of three repeated measurements in accordance with 6.5 may have one (and no more than one) of the three values of the length measurement error outside the conformance zone. Each such measurement that is out of the conformance zone (according to ISO 14253-1) shall be re-measured three times at the relevant position. If all the values of the errors of

indication of a calibrated test length with ram axis stylus tip offset of length 150 mm from the three repeated measurements are within the conformance zone ~~(see ISO 14253-1)~~, then the performance of the CMM is verified at that position.

Normative

The ISO 14253-1 decision rule cited in clause 7.1.2 is replaced by the ASME B89.7.3.1 decision rule described in Annex G.

The ISO term "conformance zone" cited in clause 7.1.2 is called the "acceptance zone" in the ASME B89.7.3.1 terminology.

Normative

7.1.3 Thermal derating of specifications

The user is responsible for providing the environment enclosing the CMM as specified by the manufacturer in the data sheet (see Annex I). Should the user fail to provide an adequate thermal environment, as measured in clause 5.1.1, then the manufacturer may, at their discretion, derate the specifications in the manner described below. The manufacturer may also (at their discretion) refuse to perform volumetric compensation in a poor thermal environment and hence if the manufacturer decides not to test the CMM in a non-conforming environment a negotiated remedy is sought. Note that failure of the user to provide the specified thermal environment may result in the acceptance of a CMM that is significantly derated in accuracy from the manufacturer's performance specifications. Thermal derating is applied only to $E_{0,\,MPE}$ and $E_{L,\,MPE}$ (and $E_{0X\,(or\,Y\,or\,Z),MPE}$ if specified). No thermal derating is applied to the repeatability test(s).

7.1.3.1 Thermal environment conformance / nonconformance

The environmental temperatures are measured according to the requirements of clause 5.1.1. For the purpose of determining environment conformance, the duration of the data collection shall be chosen by the manufacturer, not to exceed 24 hours. From the temperature measurements, the maximum and minimum observed temperatures, T_{MAX} and T_{MIN}, and the maximum temporal and absolute values of the maximum spatial gradients, ΔT_1, ΔT_{24}, ΔT_H, ΔT_V, may be found directly. Each of these is compared against its corresponding specification; see the data sheet in Annex I. If all of the observed quantities are within their corresponding specifications no derating is allowed. If any of the observed quantities exceed their specifications, then the specifications may be derated as described below.

NOTE 1   The symbol ΔT_{24} is used even if the test period is chosen to be less than 24 hours.

NOTE 2   The observed values ΔT_1, ΔT_{24}, ΔT_H, ΔT_V, are defined as the maximum of these quantities over the all the recorded temperature measurements: see 4.1.

7.1.3.2 Thermal derating warning

For any environment that significantly exceeds its specification limits, the following warnings are provided for the user. Machines that are volumetrically compensated in poor thermal environments are likely to have errors built into the compensation data tables, which may not be completely revealed by testing in the same environment. It is always best to improve the environment. Good test practice, though not always possible, is to test the machine under different poor conditions (with correspondingly derated specifications) from those present when the machine was compensated.

7.1.3.3 Thermal environment modification for spatial gradients

If either of the two spatial gradients is observed to violate the corresponding limits, temporary modification of the environment is allowed. This usually may be accomplished by such means as: placing thermal shielding, (e.g., large foam sheets and/or metal foil), between the machine and local heat sources, and stirring the air thoroughly with large fans, etc. These temporary modifications should be in place 12 hours before beginning the drift test (see 7.1.3.4.3), or any subsequent performance tests. If the modified environment now conforms to all of the thermal specifications, the rated performance specifications shall be used to determine CMM conformance. It should be noted that if temporary modifications are used, the CMM may again be out of specification when these are removed after the testing. If the modified environment has the two spatial gradient specifications conforming but any other thermal specifications are non-conforming, derated performance specifications (described below) shall be used to determine CMM conformance. However, if the modified environment is still out of specification with respect to the spatial gradient requirements then either: (1) additional modifications shall be installed to bring the spatial gradients into specification; (2) the manufacturer may refuse to perform the testing and a negotiated remedy is sought; or (3) the manufacturer may perform the testing using derated performance specifications (described below) to determine CMM conformance.

Normative

In this Report, spatial gradients that exceed their specifications are addressed only through thermal environment modification, and the derating formulas do not include spatial gradient terms addressing their nonconformance, because the impact of spatial gradients on CMMs is complex and case specific.

7.1.3.4 Thermal derating procedures

It may occur that sufficient derating of the performance specification may be achieved solely by the UNDE and NDE calculations described below. In this case, the drift test associated with the Thermal Variation Error is optional.

7.1.3.4.1 Thermal derating: uncertainty in the nominal differential expansion (UNDE)

The Uncertainty in the Nominal Differential Expansion (UNDE), ΔL_{UNDE} accounts for the length error of a test length L_{Test}, incurred due to imperfect knowledge of the coefficient of thermal expansion (CTE) of the CMM scales and the test artifact. In this Report the uncertainty of the CMM scales is fixed to 1×10^{-6} / °C, and the uncertainty in the CTE of the test length, $U(\alpha)$, is given in clauses 6.3.2 and 6.5.1, unless the method of Annex D is used where the artifact CTE is known exactly.

$$\Delta L_{UNDE} = 1 \times 10^{-6} \times L_{Test} \times \mathrm{Max}\left\{\left(T_{MAX} - T_{S\_MAX}\right), \left(T_{S\_MIN} - T_{MIN}\right), 0\right\} \text{ If the method of Annex D is used}$$

$$\Delta L_{UNDE} = \sqrt{\left(1 \times 10^{-6}\right)^2 + U(\alpha)^2} \times L_{Test} \times \mathrm{Max}\left\{\left(T_{MAX} - T_{S\_MAX}\right), \left(T_{S\_MIN} - T_{MIN}\right), 0\right\} \quad \text{otherwise}$$

NOTE ΔL_{UNDE} is never a negative number. This is because the maximum function, *Max*, serves to choose the greatest deviation of the observed temperature from the nearest specified limit, and the inclusion of 0 in the set ensures that this quantity is always non-negative.

7.1.3.4.2 Thermal derating: nominal differential expansion (NDE)

The Nominal Differential Expansion (NDE) between the CMM scales and the artifact is a measurement bias, denoted ΔL_{NDE}. This is applicable only to CMMs that do not have workpiece thermal compensation capability. (Thermal compensation is present whenever the CMM requires knowledge about the workpiece (or test length) CTE value, α, in order to perform the correction.) If the method of Annex D is used then $\alpha_{art} = 11.5 \times 10^{-6}$ / °C. The NDE bias is determined using the average temperature, T_{AVG}, which is the average of all the temperature sensors over the entire time period recorded (usually 24 hours). The effective CTE of the CMM scales, α_{scale}, is obtained from the data sheet of Annex I. (For the case where different CMM axes have different values of α_{scale}, the average of the axes in use for the TVE measurement shall be used.)

For CMMs with thermal compensation : $\quad \Delta L_{NDE} = 0$

For CMMs without thermal compensation :

$$\Delta L_{NDE} = \left(\alpha - \alpha_{scale}\right) \times L_{Test} \times \left(T_{AVG} - T_{S\_MAX}\right) \quad \text{if } T_{AVG} > T_{S\_MAX}$$

$$\Delta L_{NDE} = \left(\alpha - \alpha_{scale}\right) \times L_{Test} \times \left(T_{AVG} - T_{S\_MIN}\right) \quad \text{if } T_{AVG} < T_{S\_MIN}$$

Note: ΔL_{NDE} may be either positive or negative depending on the temperature, thermal specifications and CTEs.

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7.1.3.4.3 Thermal derating: the drift test

The drift test is performed by repeatedly measuring a suitable length artifact during a period of up to 24 hours; the artifact shall be the same as that used in the body diagonal testing of the E_0 specification. The duration of the test is chosen by the manufacturer. For the purpose of assessing the thermal drift, the longest available calibrated test length (along one of the four body diagonals, chosen by the manufacturer) is used. The longest diagonal length is chosen for maximum sensitivity to the dominant length-dependent thermal effects, but the actual derating process will scale the error in proportion to length used in each of the performance tests.

The artifact is measured in a manner similar to that described in clause 6.3, modified as follows. Put the CMM in a measurement loop to measure the artifact three times as quickly as practical. Then repeat this three-measurement cycle at least six times per hour for the duration of the drift test. For each triplet of measurements, compute the "drift test RMS deviation" to assess the length measurement repeatability during the drift test. Compute the average of the drift test RMS values over the duration of the drift test as an estimate of the contribution of system non-repeatability to the length variation observed in the drift test. Multiply this average drift test RMS by a factor of 4 to estimate a reasonable range of values due to "measurement repeatability of the drift test".

After the drift test is complete, determine the range of observed lengths. Subtract the measurement repeatability of the drift test (described above) from the observed length variation range. This difference is the thermal length variation, ΔL_T.

$$\Delta L_T = \left(L_{\text{Art MAX}} - L_{\text{Art MIN}}\right) - \frac{4}{N}\sum_{i=1}^{N}\sqrt{\frac{1}{3}\sum_{j=1}^{3}\left(L_{\text{Art ij}} - \overline{L}_{\text{Art i}}\right)^2} \ \geq 0$$

where N is the number of measurement cycles (not including the 3 repeated measurements

and $\overline{L}_{\text{Art i}} = \frac{1}{3}\sum_{j=1}^{3} L_{\text{Art ij}}$ is the mean of the 3 repeated measurements on the artefact

NOTE   The inclusion of the inequality ($\geq$) in the calculation of ΔL_T is intended to ensure that this quantity is always non-negative, i.e. if the calculation is less than zero, a value of zero will be assigned to ΔL_T.

7.1.3.4.4 Thermal derating: the thermal fractions

It is not yet practical to estimate the amount of length measurement variation that arises from a particular observed temperature environment without detailed studies of a machine beyond the scope of acceptance testing. Consequently, it is necessary to observe the actual length measurement variation (via a drift test), and then apportion that observed drift to length errors of the CMM in proportion to the amount by which particular environmental parameters have been violated. For this purpose we compute "thermal fractions" for the three effects. The sum of these fractions will multiply the observed thermal variation length, ΔL_T, and yields the thermal variation error TVE, which is a length derating formula.

In addition to the average temperature collectively biasing all length measurements, temperatures outside of the allowed limits will also introduce a range of biases into the length measurements for machines without temperature compensation. For estimating this effect we compute:

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7.1.3.4.4 Thermal derating: the thermal fractions (continued)

For CMMs with thermal compensation: $f_{NDE} = 0$

For CMMs without thermal compensation:

$$f_{NDE} = \left[\frac{\left(T_{MAX} - T_{MIN}\right) - \left(T_{S\_MAX} - T_{S\_MIN}\right)}{\left(T_{S\_MAX} - T_{S\_MIN}\right)} \right] \geq 0$$

NOTE   The requirement of $f_{NDE} \geq 0$ sets this quantity to zero if the temperature limits are not violated.

For the limitations on the rates of temperature change, represented by the two temperature variation specifications, ΔT_{S_1} and ΔT_{S_24}, the direction of the temperature change is assumed to be inconsequential.   Compute the thermal fractions as shown below; note that the thermal fraction is set equal to zero if the associated observed value is within its specification.

$$f_{\Delta T\_1} = \left[\frac{\Delta T_1 - \Delta T_{S\_1}}{\Delta T_{S\_1}} \right] \geq 0 \text{ and } f_{\Delta T\_24} = \left[\frac{\Delta T_{24} - \Delta T_{S\_24}}{\Delta T_{S\_24}} \right] \geq 0$$

Finally, compute the TVE fraction: $f_{TVE} = f_{NDE} + f_{\Delta T\_1} + f_{\Delta T\_24} \leq 1$

NOTE   The total fraction is not allowed to exceed unity, i.e., if f_{TVE} is calculated to be greater than 1.0, it is assigned a value of one.

7.1.3.4.5 The MPE thermal derating

Due to the asymmetry in the length bias arising from T_{AVG}, when the observed temperature violates the manufacturer's allowed specifications, separate expressions are needed for the derated upper and lower length measurement limits.

Compute the Thermal Variation Error: $\Delta L_{TVE} = f_{TVE} \, \Delta L_T$

The upper limit on the MPE value is adjusted by an amount, $\Delta E_{UL, MPE}$.

$$\Delta E_{UL, MPE} = \Delta L_{UNDE} + \Delta L_{NDE} + \Delta L_{TVE} \left(\frac{L_{Test}}{L_{Art}} \right)$$

Where L_{Art} is the length of the artifact used in the TVE test, and L_{Test} is the test length used in the conformance testing, i.e., there are five possible values for L_{Test}, one for each of the five test lengths; the above formula needs to be evaluated for each of these.

Similarly, the lower limit of the MPE value is adjusted by an amount, $\Delta E_{LL, MPE}$.

$$\Delta E_{LL, MPE} = - \Delta L_{UNDE} + \Delta L_{NDE} - \Delta L_{TVE} \left(\frac{L_{Test}}{L_{Art}} \right)$$

Add values of $\Delta E_{UL, MPE}$ and $\Delta E_{LL, MPE}$ to the MPE formulae as appropriate.   Then evaluate the conformance to specifications using the new MPEs.

Note: ΔL_{NDE} may be either positive or negative; ΔL_{UNDE} is always positive, and ΔL_{TVE} is always positive

7.2 Reverification test

The performance of the CMM used for measuring linear dimensions is considered to have been reverified if E_0, R_0, E_{150} described in 6.3, 6.4 and 6.5 are not greater than the maximum permissible errors $E_{0, \text{MPE}}$, $E_{150, \text{MPE}}$, and maximum permissible limit $R_{0, \text{MPL}}$ as determined in 7.1.

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Additionally, if specified, the performance of the CMM used for measuring linear dimensions is considered to have been reverified if $E_{0X \text{ (or Y or Z)}}$ and R_{Pt} values described in clauses 6.1.1 are not greater than the maximum permissible error $E_{0X \text{ (or Y or Z), MPE}}$ and maximum permissible limit $R_{\text{Pt, MPL}}$ as determined in clause 7.1

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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 etc.,

the acceptance test specified in this part of ISO 10360 may be used as a test for verifying the performance of the CMM used for measuring linear dimensions in accordance with the specification for the stated maximum permissible errors, $E_{0, \text{MPE}}$, $E_{L, \text{MPE}}$, and maximum permissible limit $R_{0, \text{MPL}}$, as agreed upon by the manufacturer and the user.

The manufacturer is permitted to specify detailed limitations applicable for $E_{0, \text{MPE}}$, $R_{0, \text{MPL}}$, and $E_{150, \text{MPE}}$. If no such specification is given, $E_{0, \text{MPE}}$, $R_{0, \text{MPL}}$, and $E_{150, \text{MPE}}$ apply for any location and orientation in the measuring volume of the CMM.

8.2   Reverification test

In an organization's internal quality assurance system, the performance verification described in this part of ISO 10360 can be used as a reverification test to verify the performance of the CMM used for measuring linear dimensions in accordance with the specification for the maximum permissible errors, $E_{0, \text{MPE}}$, $E_{150, \text{MPE}}$, and maximum permissible limit $R_{0, \text{MPL}}$ as stated by the user. The user is permitted to state the values of, and to specify detailed limitation applicable to, $E_{0, \text{MPE}}$, $R_{0, \text{MPL}}$, and $E_{150, \text{MPE}}$.

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

NOTE 2   In acceptance testing, the conformance zone is derived from the manufacturer's specifications. In reverification testing, the reverification limits may be derived from the user's metrological needs.

8.3   Interim check

In an organization's internal quality assurance system, a reduced performance verification may be used periodically to demonstrate the probability that the CMM conforms with specified requirements regarding the maximum permissible errors, $E_{0, MPE}$, $E_{150, MPE}$, and maximum permissible limit $R_{0, MPL}$. The extent of the performance verification as described in this part of ISO 10360 may be reduced by using fewer measurements and positions (see Annex A).

NOTE   This International Standard is primarily concerned with acceptance and reverification testing. Interim testing is often associated with quality assurance; see ISO 15530 series of documents for further discussion of the role of measurement uncertainty associated with CMM measurements.

9   Indication in product documentation and data sheets

The symbols of Clause 4 are not well suited for use in product documentation, drawings, data sheets etc. Table 4 gives the corresponding indications also allowed for.

Table 4 — Symbols and corresponding indication in product documentation, drawings, data sheets etc.

Symbol used in this document	Corresponding indication
E_L	EL
R_0	$R0$
$E_{L, MPE}$	MPE(EL)
$R_{0, MPL}$	MPL($R0$)

Annex A
(informative)

Interim check

A.1 Interim check of the CMM

It is strongly recommended that the CMM be checked regularly during the periods between periodic reverification. The interval between checks should be determined from the environmental conditions and the measuring performance required. The CMM should be checked immediately after any significant event that could have affected CMM performance.

Artefacts other than those calibrated test lengths that are described in Annex B may also be used in the interim test. The measurements should be made directly after the performance verification test; the positions and orientations of the artefacts should be noted and subsequently repeated.

Depending on the measurement tasks for which the CMM is being used the most relevant of the following commonly used artefacts should be chosen, some examples are given below:

— a purpose-made test piece that has features representing typical geometrical shapes, is dimensionally stable, mechanically robust, and which has a surface finish that does not significantly affect the uncertainty of measurement;

— a ball-plate;

— a hole-plate;

— a ball-bar;

— a hole-bar;

— a bar that can be kinematically located between a fixed reference sphere and the CMM probe-stylus sphere;

— a circular artefact, (e.g. a ring gauge).

It is strongly recommended that the artefact material have a coefficient of thermal expansion similar to typical workpieces measured with the CMM.

The method involving the mathematical adjustment to low CTE artefacts described in Annex D may be used in interim testing, however, it is crucial that the temperature of the low CTE artefact used for the adjustment be measured with an independent thermometer that is not part of the CMM.

A.2 Interim testing and the comparison to specifications

A.2.1 General

In some cases it may be desirable to perform an interim test in a manner where the results can be compared to the manufacturer's specifications for $E_{0,\,MPE}$, $R_{0,\,MPL}$, and $E_{L,\,MPE}$. In this case a calibrated test length, as described in Annex B, should be used and the measurement procedures described in this International Standard followed.

In order to minimize the time to perform the interim test an abbreviated test procedure should focus on those test positions that most commonly reveal a problem with the CMM. For example, the measurement of a single long test length in each of the body diagonals will generally more readily reveal CMM errors than the measurements of five test lengths along a CMM axis.

Each of the errors of indication from the interim test should be less than the corresponding specification, e.g. $E_{0,\ MPE}$, provided the test is conducted according to the procedures of this International Standard and the environmental conditions are within those stated by the manufacturer.

A.2.2 Interim testing using uni-directional artefacts

In the case where uni-directional artefacts are employed in the interim test, and minimizing the amount of testing time is important, and the comparison to manufacturer's specifications is desired, then the following procedure is useful. In this procedure the short gauge block measurements that are normally required when producing a calibrated test length using a uni-directional artefact are replaced by a combination of a single stylus form measurement, P_{FTU}, and the corresponding error of indication of sphere size P_{STU}, as described in ISO 10360-5 as shown below. The measured values of P_{FTU} and P_{STU} should be measured as part of the interim test. Then for $L = 0$ mm or $L = 150$ mm:

— If the uni-directional error is greater than or equal to zero, then E_L is approximated by the uni-directional error plus (P_{FTU} + | P_{STU} |)*;*

— If the uni-directional error is less than zero, then E_L is approximated by the uni-directional error minus (P_{FTU} + | P_{STU} |)*.*

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P_{FTU} and P_{STU} are the least-squares form error and indicated size error, respectively, of measuring a calibrated sphere with a single probe stylus using 25 measurement points: see ASME B89.4.10360.5

NOTE 1   This method of determining the error of indication is an approximation to the method specified in Clause 6 and may overestimate the error. If an error of indication in the interim test exceeds its corresponding MPE value then the position should be remeasured using the procedures specified in Clause 6.

This method is not recommended for the case of laser interferometry without contact probing measured in a unidirectional manner (B.3.3.4) because insufficient information is available to adjust the repeatability range value (see below). The two probing test results used in this method should be applicable to the stylus used to measure the unidirectional length.

When using this method to compare to the manufacturer specifications for repeatability range, i.e. $R_{0,\ MPL}$, calculate the R_0 values in the following manner:

For step gauges measured in a uni-directional manner (B.3.3.1), the repeatability range, R_0, is calculated by evaluating the range of the three repeated uni-directional length measurements and multiplying by 1,73. This also applies to laser interferometry with contact probing measured in a uni-directional manner (B.3.3.3) when the gauging surface is a plane.

NOTE 2   The multiplication factor of 1,73 compensates for the averaging of three measured points per side during the length measurement and the absence of the short gauge block measurements.

For ball plates and ball bars measured in a uni-directional manner (B.3.3.2), the repeatability range, R_0, is calculated by evaluating the range of the three repeated uni-directional length measurements and multiplying by 1,41. This also applies to laser interferometry with contact probing measured in a unidirectional manner (B.3.3.3) when the gauging surface is a sphere measured with five probing points.

NOTE 3   The multiplication factor of 1,41 compensates for the fact that each center point is derived from five specified measured points and the absence of the short gauge block measurements.

Annex B
(normative)

Artefacts that represent a calibrated test length

B.1   General

For economy, availability, and practicality, it is the intent of this International Standard to allow several types of artefacts to be used in testing a CMM provided they are appropriately adjusted (as described in this annex) to yield the same measurand, a calibrated test length.

A calibrated test length, as measured by the procedures of this International Standard, is designed to detect three categories of CMM errors:

1)   geometrical and thermal errors associated with the CMM between the two end points of the test length,

2)   stylus tip size errors, and

3)   repeatability problems as evaluated, in effect, by a single probing point on each end of the calibrated test length.

B.2 and B.3 describe common artefacts that may be used as a calibrated test length. In some cases these artefacts may not be available or sufficiently long, particularly when testing very large CMMs. In this case both parties may agree to use other means to generate a calibrated test length, this might include length standards that are "stitched" together (i.e. overlapped end-to-end) to form a longer artefact, or other types of laser-based lengths, e.g. produced by multilateration. In the latter case, issues associated with the absence of contact probing must be accounted for (see B.3). In all such cases the procedure shall be documented and the uncertainties associated with these techniques shall be considered carefully.

A laser interferometer that is corrected for the index of refraction of air has a zero CTE (α = 0). Hence, if it is used to produce a calibrated test length it is considered a low CTE material and is subject to 6.3.3.3. Additionally, if the laser has a workpiece (material) temperature sensor, then the workpiece CTE in the laser's software shall be set to 0. If a laser is used on a temperature compensated CMM, then the workpiece CTE in the CMMs software shall be set to 0.

NOTE   When a laser interferometer is used to produce a calibrated test length, the CMM has to be positioned at a point described by nominal coordinates, without probing a surface. In this case, some CMMs may not arrive at the nominal position exactly. This does not necessarily result in an error of indication as long as the CMM reports the actual position. Consequently, for each test length, the spatial distance between the reported CMM coordinates of points A and B has to be evaluated and compared with the distance indicated by the laser interferometer. It has to be assured, that the CMM coordinates used for the calculation of the error include all compensations that would be considered during the probing process.

Some artefacts such as step gauges, multi-ball bar bars, ball plates, and laser interferometry can produce multiple lengths relative to a "reference zero". For example, a step gauge can measure lengths "A" to "B", "A" to "C" etc, or an interferometer can measure the displacement from an initial position to a series of subsequent positions (each of different length). In order to provide equivalency to gauge blocks, the reference position, i.e. the "zero", must be remeasured each time a calibrated test length is produced. That is, the "A" to "B" length and the "A" to "C" length each must have its own "A" measured anew. Similarly with interferometry, the initial position must be remeasured for each displacement used to produce a calibrated test length.

B.2   Bi-directional measurements

B.2.1 General

Bi-directional measurements of calibrated gauges represent a calibrated test length. A bi-directional measurement involves probing a single point on each end of the gauge, and that these probing points are approached from diametrically opposite directions; see Figure B.1. Internal and external bi-directional measurements shall not be mixed on a measurement line. Several possible bi-directional measurement methods are described below.

a) gauge block   b) step gauge   c) ball bar (endpoint-to-endpoint measurement)   d) laser
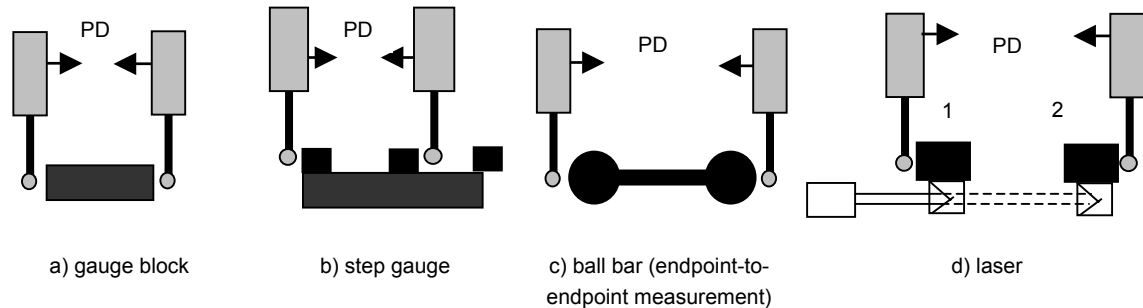
Key
PD Probing direction
1   Position 1
2   Position 2

Figure B.1 — Examples of bi-directional measurements each probed with a single point in each direction

B.2.2 Gauge blocks

A calibrated test length may be produced using a calibrated gauge block measured with a single-point-to-single-point method. It is advised that each probing point be located at the calibrated gauging point for the block. See Annex C for alignment procedures.

B.2.3 Step gauges measured in a bi-directional manner

A calibrated test length may be produced using a calibrated step gauge measured with a single-point-to-single-point bi-directional method; see Figure B.1. See Annex C for alignment procedures.

B.2.4 Ball bars / ball plates measured in a bi-directional manner

A calibrated test length may be produced using a ball bar/ball plate where the length is equal to the calibrated sphere center-to-center length plus one half the calibrated diameter of each sphere. The gauge is measured in a single-point-to-single-point, bi-directional manner (identical to a gauge block). See Annex C for alignment procedures.

B.2.5 Laser interferometry with contact probing measured in a bi-directional manner

A calibrated test length can be produced using a laser interferometer and a gauge block. The calibrated test length is the sum of the calibrated length of the gauge block and the displacement recorded by a calibrated laser interferometer system. The gauge block is measured with a single point at the initial position and then the opposite face of the gauge block is measured with a single point at the second position; see Figure B.1.
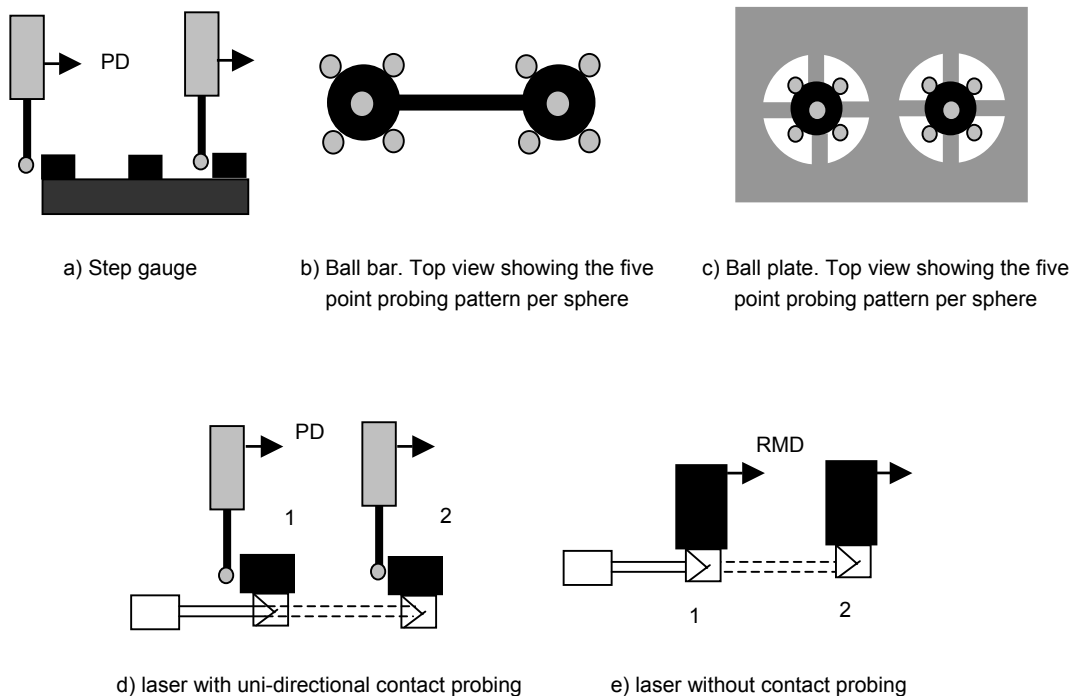
B.3 Uni-directional measurements (must be supplemented with bi-directional measurements)

B.3.1 General

For purposes of this International Standard uni-directional measurements are any measurements that are not bi-directional. They include step gauges measured in a uni-directional manner, center-to-center distances of ball plates and ball bars, and some methods of laser interferometry; see Figure B.2.

Uni-directional measurements must be combined with bi-directional measurements in order to produce a calibrated test length for testing purposes of this International Standard.

A calibrated test length can be produced using the arithmetic sum of a calibrated uni-directional length and a calibrated bi-directional length (default is a short gauge block) with the bi-directional length measured in a single point-to-point manner.

| a) Step gauge | b) Ball bar. Top view showing the five point probing pattern per sphere | c) Ball plate. Top view showing the five point probing pattern per sphere |

d) laser with uni-directional contact probing   e) laser without contact probing

Key
PD   Probing direction
PMD   Ram motion direction
1   Position 1
2   Position 2

Figure B.2 — Examples of uni-directional measurements

B.3.2 Calibrated test length composed of uni-directional and short gauge block measurements

For each measurement line under testing (there are seven lines for the E_0 test and up to two lines out of a possible four lines for the E_{150} test) measure a short (default 25 mm) calibrated gauge block in a bi-directional manner as described in B.2.2.

The gauge block shall be oriented along the measurement line, i.e. the gauge block axis shall be approximately in the same direction as the measurement line under testing. The location of the gauge block shall be as close as possible to the measurement line under testing, however, for ease of fixturing, the block may be located near the CMM table surface.

For example, if a body diagonal of the CMM is the measurement line under testing, then the gauge block shall be oriented along the direction of the body diagonal, but may be located "beneath" the diagonal and fixtured near the table surface.

The short gauge block shall be measured a total of three times and the errors of indication recorded in their chronological order. In the special case of the E_{150} test when the same measurement line is measured with two diametrically oriented probes, the three short gauge block measurements shall be measured with one probe orientation then repeated with the opposite probe orientation.

For each of the five lengths (per measurement line) measure a calibrated uni-directional length three times and record the errors of indication in chronological order; details for specific types of uni-directional lengths are described in B.3.3.

To each of the three uni-directional errors of indication add (in the usual arithmetical manner) the chronologically corresponding bi-directional errors of indication to create the errors of indication of the calibrated test lengths. Repeat for all five lengths per measurement line; this involves a total of 15 uni-directional measurements and three bi-directional (short gauge block) measurements per measurement line.

NOTE   The test results are affected by the position of the short gauge block, e.g., locating the gauge block near the CMM table may alter the test performance due to the CMM behaviour when the ram is fully extended. The intended representation of the CMM performance is approximated by locating the short gauge block in the middle of the measuring line. However this may cause fixturing problems. It is up to the tester to choose the best compromise.

An alternative to the short gauge block is to measure a small sphere of calibrated diameter (default of 25 mm) in a bi-directional manner as follows. Two points shall be located at opposite points of a sphere diameter that is oriented parallel to the measurement line. The other two points shall be spaced 90 degrees apart, located on the sphere and in a plane orthogonal to the measurement line and containing the sphere center. The sphere diameter measured in this manner is equivalent to a bi-directional short gauge block measurement.

This alternative method may be used upon agreement of user and manufacturer; otherwise the short gauge block shall be used.

B.3.3 Artefacts for uni-directional measurements

B.3.3.1   Step gauges measured in a uni-directional manner

 A uni-directional measurement of a step gauge shall have each gauging surface measured with three discrete points (at the same target contact point) and the coordinates averaged.

The length is determined using the averaged coordinates. The measurement shall be done in a uni-directional manner (see Figure B.2). See Annex C for alignment procedures.

NOTE   The averaging of three points on each gauging surface of a uni-directional step gauge is needed, when combined with the short gauge block errors, to have the test results be equivalent to that of the single-point-to-single-point bi-directional measurement case.

B.3.3.2   Ball plates and ball bars measured in a uni-directional manner

A uni-directional measurement of an artefact with spherical gauging surfaces, such as a ball plate or ball bar, consists of each sphere measured with five probing points and the (least squares fit) center-to-center length determined.

The point sampling strategy is shown in Figure B.2.

B.3.3.3   Laser interferometry with contact probing measured in a uni-directional manner

A uni-directional measurement can be produced using a calibrated laser interferometer and a gauging surface; the gauging surface may be a plane or a sphere.

The measurement involves interferometrically measuring the displacement of the gauging surface that is (contact) probed by the CMM. The gauging surface is typically moved on a carriage or sled that has an attached laser retroreflector.

In the case where the gauging surface is a sphere, the sphere center location shall be measured with five points as described in B.3.3.2. In the case of a plane the surface is probed with three points at each position and the coordinates averaged as described in B.3.3.1, the probing direction is the same for both the initial and final positions, see Figure B.2.

B.3.3.4   Laser interferometry without contact probing measured in a uni-directional manner

In some cases (particularly large CMMs) it may be convenient to replace the probing system with a retroreflector and to measure the displacement of the CMM using laser interferometry.

Each laser displacement measurement is considered a uni-directional measurement, see Figure B.2.

NOTE   For some CMMs tested with laser interferometry used without contact probing, the interferometric measurements may not appropriately implement the CMM compensation for geometrical errors. Consequently, this will yield an error of indication much larger than would be the case with contact probing. In such cases a calibrated test length involving contact probing should be employed. In this case an external trigger activating the error compensation may alleviate the problem.

Annex C
(informative)

Alignment of gauges

C.1 General

To compare the length measured by a CMM to the calibrated value of the test length it is necessary to properly align the test length. If the calibration certificate of the test length supplies instructions for alignment then those instructions should be followed prior to the length measurements. In the absence of alignment instructions in the calibration certificate the manufacturer may decide the alignment procedure.

C.2 Parallel face gauges

For parallel face gauges the following alignment procedure may be useful.

Probe many points on one gauge face and establish a (least squares fit) reference plane. The direction perpendicular to the plane is the reference (gauge axis) direction. Measure a single point on each gauging face, e.g. on each end of a gauge block, with each point taken as close as possible to the calibration point on the gauge. Construct the point-to-point length and then project this length onto the reference (gauge axis) direction. The projected length is then compared to the calibrated value of the gauge.

For some gauges that are very long relative to the size of the gauging faces, e.g. when the calibrated test length is greater than 10 times the size of the gauging face, the reference direction may be established using points on the non-gauging surfaces of the gauge. For example, measuring points on the two long sides of a gauge block can be used to establish the reference (gauge axis) direction. This alignment technique should also be used for step gauges, if there is no alignment procedure in the calibration certificate.

The single point measured on each gauging surface is then used to construct a point-to-point length that is then projected onto the reference direction. This projected length is then compared to the calibrated value of the gauge.

C.3 Ball bar/ball plate gauges

One method of aligning ball bars or ball plates when they are measured in a bi-directional manner is to ensure that the probe approach direction is along the gauge axis, i.e., the line passing through the sphere centers. The gauge axis is defined as the center-to-center axis between the two spheres. Due to the alignment method, this type of calibrated test length shall only be used on CMMs where the probe approach motion is under computer control.

Another method of aligning ball bars or ball plates when they are measured in a bi-directional manner is to measure each sphere using four points, one point located on the sphere, intersecting the gauge axis (i.e., endpoint), and the other three points spaced 90 degrees apart, located on the sphere and in a plane orthogonal to the gauge axis and containing the sphere center (i.e., points on the equator). These three points serve to align the ball bar or ball plate. See Figure C.1.

In both cases the bi-directional ball bar or ball plate measurement defines a calibrated test length that consists of the calibrated center-to-center distance plus one half the calibrated diameter of each sphere.
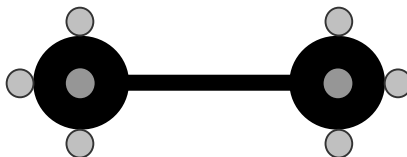

Figure C.1 — View showing a four point probing pattern per sphere used for a bi-directional ball bar measurement

Ball bars or ball plates measured in the uni-directional (sphere center-to-center) manner have a geometrically unique center location of each sphere and consequently typically do not require special alignment methods.

NOTE 1   When using ball bars or ball plates, it has to be assured that the probing pattern during the test is as close as possible to the probing pattern documented in the calibration certificate of the standard and that it is similar to the pattern shown in Figure B.2. If this cannot be achieved the pattern in Figure B.2 shall be used and additional contributors to the test uncertainty must be considered.

NOTE 2   For measuring a bi-directional ball bar, only computer controlled CMMs should be used. Follow the artefact's alignment procedures, typically by first determining the gauge axis by measuring the two spheres before performing the bi-directional measurement.

NOTE 3   In the case of some multi-ball ball bars, a common measurement axis does not exist. In some cases only the center distance between two neighbouring balls is calibrated. For lengths comprised of two non-adjacent balls, the reference value is taken as the sum of spatial distances; because of the geometry of the intervening sphere locations, additional uncertainties associated with this geometry should be taken into account (see Figure C.2).
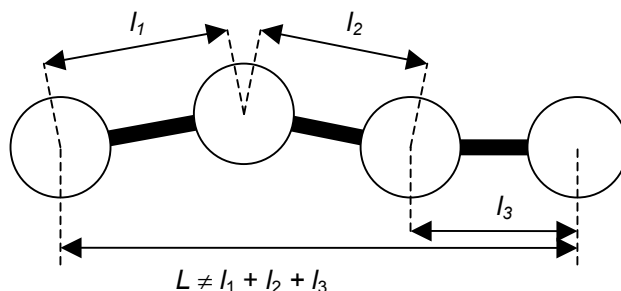

Figure C.2 — Evaluation of ball distances for a multi-ball ball bar

Annex D
(normative)

Mathematical adjustments to Low CTE artefacts

D.1 General

In some situations a mathematical adjustment to account for thermal expansion is advantageous to facilitate CMM testing.

Consider a large CMM that is made of steel, used to measure steel parts, and the CMM does not have any method to account for workpiece thermal expansion. Such a large CMM requires a long calibrated test length and hence thermal equilibrium of the test length is important for normal CTE artefacts. To reduce the effect of non-equilibrium thermal conditions, a low CTE test length may be used.

However, a low CTE test length will have a large uncorrected thermal expansion difference between the test length and the (normal CTE) CMM. Hence large length measurement errors, e.g. the E_0 values, will be observed that are not characteristic of errors when measuring steel workpieces. Consequently, it may be advantageous to perform a mathematical adjustment to the calibrated length of the low CTE artefact making it appear to the CMM as if it were steel.

Implementing such an adjustment requires the low CTE test length to have its temperature measured once at the beginning of each test (E_0 and E_{150}) using a calibrated thermometer. This temperature is used to calculate a "synthetic length" equivalent to a steel gauge with an exactly known CTE, $\alpha = 11,5 \times 10^{-6}$ /°C. The effect of this adjustment is to change the calibration of the low CTE test length such that it corresponds to a synthetic length, with a CTE of $11,5 \times 10^{-6}$ /°C, at the measured temperature. In the example given above, the advantage of this procedure is that the steel CMM will be measuring a "synthetic steel" test length and hence not suffer the uncorrected thermal expansion error.

NOTE   The mathematical adjustment to the low CTE artefact is performed by the tester according to the requirements of D.2. This adjustment is equivalent to a recalibration of the artefact and does not violate the prohibition of manual corrections of CMM measurement results described in 6.3.4. and 6.5.3.

D.2 Requirements

When implementing the mathematical adjustment procedure for acceptance or reverification testing several issues must be observed:

⎯   The mathematical adjustment is only permitted on CMMs that do not have the capability for workpiece thermal expansion compensation;

⎯   The mathematical adjustment is only permitted on artefacts with a CTE of 2×10^{-6} /°C or less;

⎯   The actual CTE of the artefact must be stated on its calibration certificate prior to any measurements performed on the CMM;

— The mathematical adjustment will be to a CTE of $11{,}5 \times 10^{-6}$ /°C exactly, and no other synthetic CTE may be used;

— The mathematical adjustment may be performed only once for the E_0 test and only once (with a new temperature measurement) for the E_{150} test. In each case the temperature measurement shall occur before the beginning of each test;

— The low CTE test length must be measured with a calibrated thermometer and not using any temperature measuring system supplied with the CMM;

— This adjustment is subject to the requirements of a low CTE artefact as described in 6.3.3.3 and the additional test length described in 6.3.3.3 must be implemented;

— The temperature measurement used in the adjustment must be taken on the steel gauge block described in 6.3.3.3 that has reached equilibrium with its environment, or a thermally equivalent piece of steel;

— When employing the mathematical adjustment procedure both the CTE of the test length and its synthetic CTE shall be stated on the test results page, e.g., "CTE of test length is $0{,}5 \times 10^{-6}$ /°C mathematically adjusted to $11{,}5 \times 10^{-6}$ /°C".

NOTE   The effects of thermal gradients in the calibrated test length are greatly suppressed when using a low CTE artefact, but these effects may appear as length measurement errors when using a normal, e.g. steel, artefact.

Annex E
Normative
Test Uncertainty

E.1   General

This Annex provides guidance on evaluating the uncertainty associated with observed errors when values indicated by a CMM are compared with calibrated test lengths. Suitable calibrated test lengths include gauge blocks, step gauges, ball bars, ball plates, and a laser displacement interferometer. When unidirectional lengths are measured they must be combined with a gauge block to form a calibrated test length, see Annex B. Simple linear measurement models are presented, together with discussions of the significant sources of test measurement errors and methods of evaluating the corresponding uncertainty components.

This Annex focuses on the calculation of an expanded uncertainty associated with the testing equipment. This $k = 2$ expanded uncertainty, called the test uncertainty, is defined as $U(E_L) = 2u(E_L)$, where $u(E_L)$ is the combined standard uncertainty associated with the observed error of indication, evaluated according to the principles of the GUM. Applications of the test uncertainty in this Report include the calculation of the measurement capability index, C_m, discussed in Annex G, which is the ratio of the zone defined by the manufacturer's MPE specification, i.e. $\pm E_{L,\,MPE} = 2\,E_{L,\,MPE}$, to two times the test uncertainty. Hence in this Report, $C_m = (2\,E_{L,\,MPE})\,/\,(2\,U(E_L))) = E_{L,\,MPE}\,/\,(U(E_L))$. Additionally, Annex F discusses the requirements for the traceability of the calibrated artifact used in the testing procedure. One of the traceability requirements includes a statement of the expanded ($k = 2$) uncertainty of the test length at the time of use. This is just the test uncertainty $U(E_L)$.

As stated in clause 6.1, there may exist situations where the user wishes to utilize their own artifact(s) for the purposes of CMM testing. To determine whether this is permitted, both the manufacturer and the user must calculate the test uncertainty that will be present when performing the acceptance tests using their respective artifacts. It is recommended that these calculations be performed, and the test uncertainty values be agreed upon, as part of the contract negotiations prior to the CMM testing.

E.1.1   Test reproducibility and test uncertainty

In this Report, the decision rule (see Annex G) used to determine conformance to specifications only addresses the uncertainty of the testing equipment, known as "test uncertainty". Test uncertainty is associated with those uncertainty sources that arise solely from the testing equipment, and are not associated with the CMM. (Inaccuracy of the CMM is controlled by its specifications.)

Variations in the result of a performance test, i.e. test reproducibility, may arise from many factors, most of which do not involve test uncertainty. The number of measurements required in this Report is a trade-off between thoroughness and practical and economical implementation of the tests. Two measurements carried out on the same CMM on the same "perfect" (one having zero test uncertainty) calibrated artifact may lead to different errors of indication E_L, for the following reasons:

a)   choice of test locations: the purchaser (for the acceptance test) is allowed to decide on some of the locations of the calibrated test lengths in the CMM volume (see clauses 6.3.3.1 and 6.5.2). A test result can be very sensitive to the choice of these locations; for instance, a location along a volumetric diagonal usually provides a more severe test than along a CMM axis. As a result, a different choice of location may lead to different errors of indication.

b)   environmental conditions: the test is performed in an environment that complies with the CMM manufacturer's specifications, usually expressed as ranges of thermal parameters. In practice, the actual test is performed in a particular condition only, as it is usually impossible, for time and cost reasons, to repeat the test many times while varying temperatures, gradients, vibrations, etc. The strong sensitivity of CMM performance to the environmental conditions is well known; as a result, the environment affects the test result significantly. For instance, a CMM specified to work

in the temperature range 18 °C to 25 °C is very likely to achieve much smaller errors of indications when the temperature during the test is 20 °C than when it is 25 °C.

c) CMM repeatability: repeated measurements of the same artifact lead to slightly different results due to such factors as probing noise, vibrations, backlash, etc. As each calibrated reference length is measured in each location only three times, the statistics are poor, and further measurements might lead to different errors of indication. This problem stems from the stipulated test procedure, which specifies the number of repeated measurements, and allows the test to be performed just once if the manufacturer's environmental specifications are met. The rationale for this is a trade-off in the interest of economic feasibility, based on educated experience that most CMM behavior is captured by this test, and with the awareness that more extensive coverage could only be achieved at an unacceptable cost.

Therefore, the errors caused by the test reproducibility are not part of the tester's responsibility, and no uncertainty component due to reproducibility is included in the test uncertainty. However, components that directly cause uncertainty in the tester's equipment due to the tester's practices, such as avoidable heating of a test artifact, are the tester's responsibility.

E.2   Length measurement tests

In a typical length measurement test, a calibrated test length is measured by a CMM. The measurand of interest is the error of indication E_L, defined to be the difference between the length indicated by the CMM and the calibrated test length.

The test uncertainty $U(E_L)$ associated with an observed error of indication can be evaluated following the standard procedure described in the GUM, given an appropriate model of the test measurement. The particular measurement model will depend on the method chosen to realize a calibrated test length, as described in Annex B. Several methods are analyzed below.

E.2.1   Bi-directional gauge blocks and step gauges

The error of indication when measuring a gauge block or step gauge is modeled by

$$E_L = (x_{ind} - e_T - e_\alpha) - x_{cal} + c_{align} + c_{fix} ,$$

where

x_{ind} is the length indicated by the CMM;

e_T is an error in indicated length due to an error in artifact temperature supplied by the tester;

e_α is an error in indicated length due to an error in artifact CTE supplied by the tester;

x_{cal} is the calibrated length of the gauge block or step gauge;

c_{align} is a correction for misalignment of the test artifact; and

c_{fix} is a correction for alignment distortion due to fixturing.

The combined standard uncertainty $u(E_L)$ for the simple linear model is found by adding the contributing standard uncertainty components in quadrature. The test uncertainty is then given by $U(E_L) = 2u(E_L)$.

The measured length x_{ind} reported by the CMM is taken to be a fixed constant so that

$$u^2(E_L) = u^2(e_T) + u^2(e_\alpha) + u^2(x_{cal}) + u^2(c_{align}) + u^2(c_{fix}).$$

A thermally compensated CMM indicates the length of the artifact at 20 °C. The CMM calculates this length by multiplying the measured length at temperature T by $1 - \alpha(T - 20\,°C)$. If the temperature is supplied by the tester using his own thermometers, and if the temperature is in error by an amount

δT, then the indication will be in error by an amount $e_T = -\alpha x_{cal} \delta T$. The associated uncertainty component is $u(e_T) = \alpha x_{cal} u(T)$, where $u(T)$ is the standard uncertainty of the measured temperature. This becomes part of the test uncertainty since it arises from information supplied by the tester.

If the CMM requires the tester to input an artifact CTE α, and if α is in error by an amount $\delta\alpha$, then the indicated length will be in error by an amount $e_\alpha = -x_{cal} \delta\alpha(T - 20\,°C)$. The associated uncertainty component is $u(e_\alpha) = x_{cal}(T - 20\,°C)u(\alpha)$, where $u(\alpha)$ is the standard uncertainty of the artifact CTE. This becomes part of the test uncertainty since it arises from information supplied by the tester.

If the tester does not supply temperature information, then $u(T)$ is taken to be zero; this will be the case if the CMM has thermal compensation and includes its own thermometers or if the CMM does not have thermal compensation and hence no temperature information is needed. If the tester does not supply CTE information, then $u(\alpha)$ is taken equal to zero; this will be the case if the CMM does not have thermal compensation and hence no CTE information is needed .
The test uncertainty then becomes

$$U(E_L) = 2u(E_L) = 2\sqrt{u^2(x_{cal}) + (\alpha x_{cal})^2 u^2(T) + [x_{cal}(T - 20\,°C)]^2 u^2(\alpha) + u^2(c_{align}) + u^2(c_{fix})}.$$

Test uncertainty using a gauge block or step gauge to realize a test length.

The following sections provide guidance on the evaluation of the uncertainty components.

E.2.1.1   Calibration standard uncertainty, $u(x_{cal})$
A GUM compliant calibration certificate for the test length will state the expanded uncertainty U_{cal} and the coverage factor k used (typically $k = 2$). The uncertainty component $u(x_{cal})$ is obtained by dividing the expanded uncertainty by the coverage factor,

$$u(x_{cal}) = \frac{U_{cal}}{k}$$

In a test where two or more gauge blocks are wrung together to achieve a desired length, the individual uncertainties must be combined, taking into account possible correlations. In a typical situation where the gauge blocks are taken from the same set, calibrated by the same laboratory at the same time, the correlation may be significant, and a linear, rather than quadratic, summation may be a wise choice. Otherwise, the correlation should be investigated and properly treated.

E.2.1.2   Artifact temperature standard uncertainty, $u(T)$
This uncertainty component shall be included only for CMMs with thermal compensation and only when that compensation relies on the temperature of the artifact as measured by the tester by means of the tester's own thermometers. For CMMs with thermal compensation where the temperature is measured by means of thermometers supplied with the CMM, and for CMMs without thermal compensation, $u(T)$ should be set equal to zero.

Temperature measurement errors may arise from several sources:

a)   Calibration errors of the tester's thermometer(s).
b)   Temperature variations during the test. The error is due to different time constants of the test artifact and the thermometer(s), the propagation time from the artifact surface in contact with the environment to the core.
c)   Radiation from the environment to the thermometer(s) and thermal contact with the test artifact.
d)   A thermal gradient along the test artifact, which affects the measured value of the average temperature.

The following steps can help to reduce thermal errors:

a) The calibration uncertainty of the thermometer(s) should be appropriate for the actual measurement requirement; when this uncertainty component is dominant in the test uncertainty budget, consider a better calibration.
b) Thermal contact is improved by matching surface geometries (e.g. flat on flat) and by use of a heat sink grease.
c) Radiation can be blocked by reflecting shields. The tester is advised to shield the thermometer(s), e.g. by means of an insulating material wrapped in aluminum foil, and to contact the thermometer(s) to the test artifact with a thermal contact grease formulated to improve thermal contact.
d) To minimize the effect of thermal gradients, the tester is advised to wait for a proper settling time before measuring. Whenever possible, the use of two thermometers is recommended, symmetrically located about the midpoint of test artifact, at a distance approximately 0.25 L from the ends. The mean value should be used as the effective temperature. If only one thermometer is available, it is recommended that it be placed at the midpoint of the material standard of size, and to wait for an additional settling time.

To evaluate the standard uncertainty $u(T)$, the following components may be considered:

a) The calibration uncertainty of the tester's thermometer(s) as reported on the calibration certificate of the thermometer(s). Remember to transform the expanded uncertainty U reported in the certificate into the standard uncertainty $u(T)$ by dividing by the coverage factor k, $u(T) = U/k$; the value of k is also reported in the certificate, the most common value being $k = 2$.
b) The uncertainty due to temperature variation during the test is best derived from experience with standards of similar thermal properties. If no sufficient experience exists, the approximate value $\Delta T_{max}/\sqrt{3}$ is recommended, where ΔT_{max} the estimated maximum temperature difference between a temperature sensor and any other point on or in the calibrated test artifact.

E.2.1.3 Artifact CTE standard uncertainty, $u(\alpha)$
This uncertainty component should be included only when the CMM requires the tester to input a CTE value. For CMMs without thermal compensation, $u(\alpha)$ should be set equal to zero.

To evaluate the standard uncertainty $u(\alpha)$, the following guidelines are suggested:

— If the calibrated test length has also been calibrated for its CTE, the uncertainty reported on the calibration certificate should be used. Remember to transform the expanded uncertainty U reported on the certificate into the standard uncertainty $u(\alpha)$ by dividing by the coverage factor k, $u(\alpha) = U/k$; the value of k is also reported in the certificate, the most common value being $k = 2$.
— If the CTE of the test artifact has not been calibrated, technical literature may report a typical range of values for the material of the artifact; if so, the range $\alpha_{max} - \alpha_{min}$ should be divided by the square root of 12 to give the standard uncertainty $u(\alpha) = (\alpha_{max} - \alpha_{min})/\sqrt{12}$.
— In the particular case of steel gauge blocks, ISO 3650 specifies a range $\alpha = (11.5 \pm 1) \cdot 10^{-6}$ /°C, and therefore a value of $u(\alpha) = 0.58 \cdot 10^{-6}$ /°C should be assumed if no individual calibration value is available.

E.2.1.4 Artifact alignment standard uncertainty, $u(c_{align})$
General guidance on the alignment of calibrated test lengths is given in Annex C. Following good metrological practice and using test length artifacts of high quality can reduce the alignment uncertainty to a negligible level, so that $u(c_{align}) \approx 0$.

In case of doubt in particular circumstances, the following discussion expands on the more general remarks of Annex C.

Misalignment errors may occur due to the following causes:

a) non-identical definitions of the axis of the test artifact during calibration and during CMM testing. A gauge block, for example, is calibrated mechanically between the centers of the measuring faces but might be aligned for testing by probing one of the side faces;
b) imperfect alignment of a test artifact due to probing errors and form deviations of the test artifact; for example, a step gauge is aligned on its side faces which have poor surface finish and/or flatness errors;
c) positional errors of the CMM in probing the two end points, i.e. the actual contact points differ from the target contact points; for example, either the CNC or the tester (for manual CMMs) drives the stylus tip imperfectly.

The following is recommended to reduce these effects:

a) significant form errors, e.g. perpendicularity errors between the side and measuring faces. It is recommended to align the axes of each test artifact separately, even when multiple artifacts are mounted together to speed up the test, e.g. gauge blocks.
b) the sampling strategy of the datums used to define the axis of the test artifact should be carefully designed. Parts of the surface with good finish are preferred. Care should be taken to minimize the effects of form errors (e.g. by exploiting expected symmetries of the form errors) and to avoid ill-conditioned datums (i.e. small probing errors resulting in large orientation errors). As an example, a test artifact aligned on its side faces is best sampled symmetrically about the center to minimize the misalignment effect of bending (form error), and at points as far from each other as possible, e.g. at the extremes, to optimize the angular definition of the associated line or plane.
c) positional error is unavoidable both for CNC and manual CMMs, but most of its effect can be filtered out. It is recommended to project the measured end points onto the axis of the artifact before calculating the distance between them. When the axis of the artifact is taken as an axis of a workpiece coordinate system, then this is easily done by taking the difference of the two point coordinates along that axis.

Misalignment results in two different errors, arising from:

— confusing a hypotenuse of a triangle (the measured quantity) with a side of a triangle (the measurand), often referred to as cosine error
— lack of parallelism of the measuring faces, giving different values for measurements along parallel lines.

Corrections for these two errors are separate terms in the approximate model below, recommended for the misalignment error:

$$c_{align} = c_{cos} + c_{parallel}$$

$$\text{with} \quad c_{cos} = \frac{\theta^2}{2}L, \quad \theta = \frac{(p_1 + p_{geo1}) - (p_2 + p_{geo2})}{L_{align}}$$

where:

c_{cos}	is the cosine error
$c_{parallel}$	is the parallelism error of the measuring faces of the test artifact
θ	is the misalignment angle
L	is the nominal length of the test artifact being measured
p_1, p_2	are unidirectional probing errors, in the direction of probing the alignment points
p_{geo1}, p_{geo2}	are the form errors at the alignment points, i.e. their lateral deviations from the axis of the test artifact defined during calibration
L_{align}	is the distance between the alignment points defining the angular direction with the largest uncertainty

NOTE 1   Misalignment actually occurs in space (3D). It is modeled here in a plane (2D) for sake of simplicity. In case of a gauge block aligned on a measuring face, L_{align} is the distance between the probed points along the shortest side on that face (typically a few millimeters).

NOTE 2   When the definition of the axis of the test artifact is the same as that used during calibration, the errors p_{geo1} and p_{geo2} are zero.

NOTE 3   In the case of gauge blocks, the axis of the test artifact is defined in ISO 3650 as normal to one of the measuring faces. When the side faces are used instead for alignment, p_{geo1} and p_{geo2} are the perpendicularity errors (ISO 3650, clause 7.4.3) at the points used for alignment.

NOTE 4   When the alignment is based on a side face, L_{align} is usually slightly shorter than the side face size ($L_{align} \approx L$ for gauge blocks), and $u(p_{geo})$ can be derived from the specification of the test artifact.

NOTE 5   For those CMMs which compensate the measured distance, rather than each point, for the stylus tip diameter, the size L in the first term of the above equation is an approximation of the more correct ($L \pm D$), where D is the stylus tip diameter, and the plus or minus sign depends on whether the measurement is external or internal. This approximation is usually acceptable, unless the shortest measured size is much shorter than the prescribed 30 mm and a large stylus tip is used.

An approximation to the standard uncertainty component $u(c_{align})$ is calculated as

$$u\left(c_{align}\right) = \sqrt{u^2\left(c_{cos}\right) + u^2\left(c_{parallel}\right)}$$

with $u\left(c_{cos}\right) = 2\sqrt{2}\,\dfrac{u^2\left(p\right) + u^2\left(p_{geo}\right)}{L_{align}^2}L.$

Where:

$u(p) = u(p_1) = u(p_2)$ is the standard uncertainty of the unidirectional probing error

$u(p_{geo}) = u(p_{geo1}) = u(p_{geo2})$ is the standard uncertainty of the form errors at the alignment points, due to their lateral deviations from the axis of the material standard of size defined for calibration

$u(c_{parallel})$ is the parallelism standard uncertainty

NOTE 6 It is assumed that the uncertainties of p_1, p_2 and of p_{geo1}, p_{geo2}, respectively, at the alignment points are equal.

NOTE 7 The cosine error is always positive and hence cannot have a mean of zero. A rigorous application of the GUM would require a systematic correction (GUM clause F.2.4.4), which is usually impractical. The expression given above requires no correction but overestimates the cosine uncertainty by 41%.

NOTE 8 The effect of an error in L_{align} is second order and thus negligible.

Illustrative values of relative uncertainty $u(c_{cos})/L$ due to cosine error are given in Table E.1.

Table E.1 – Relative uncertainty $[u(c_{cos})/L]\cdot 10^6$ due to the cosine error.

		L_{align} /mm			
$u(p_{geo})$ /µm	$u(p)$/µm	6	30	250	500
0	1	0.08	0.00	0.00	0.00
	5	1.96	0.08	0.00	0.00
50	≤ 5	198	7.94	0.11	0.03
100	≤ 5	788	31.5	0.45	0.11
A value of e.g. 1.96 in the table means $u(e_{cos}) = 1.96\cdot 10^{-6}\,L$					

To evaluate the input uncertainties, the following is suggested:

a) $u(p)$ is the unidirectional repeatability of the CMM. It can be evaluated either as the sample standard deviation s of repeated unidirectional measurement of a plane surface, $u(p) = s$ (type A evaluation), or as a fraction of the probing error P, $u(p) = P / \sqrt{12}$ (type B evaluation). The latter is likely to overestimate this input uncertainty, since P is derived from multi-directional measurements. If the standard uncertainty obtained is considered too large, repeatedly probing the alignment points reduces this uncertainty by averaging, namely $u(p) = u_{\text{single}}(p) / \sqrt{n}$, where $u_{\text{single}}(p)$ is the standard uncertainty obtained for a single probing cycle, and n is the number of probing cycles.

b) $u(p_{\text{geo}})$ is non-zero only when the definition of the axis of the test artifact is not the same as that used for calibration. In this case, it can be derived from the tolerance T specified on the surface of the artifact used for alignment, with the axis used for calibration as a datum, viz. $u(p_{\text{geo}}) = T / \sqrt{12}$. For gauge blocks, T is the perpendicularity tolerance, and its value is set in ISO 3650, Table 4.

c) $u(c_{\text{parallel}})$ can be derived from the parallelism tolerance $T_{//}$ set on the measuring faces of the material standard of size, viz. $u(c_{\text{parallel}}) = T_{//} / \sqrt{12}$. For gauge blocks, $T_{//}$ is the tolerance of the variation in length and its value is specified in ISO 3650, Table 5. This value of $u(c_{\text{parallel}})$ is likely overestimated, as the area where the axis of the gauge block intersects a measuring face is usually significantly smaller than the measuring face.

E.2.1.5   Fixturing standard uncertainty, $u(c_{\text{fix}})$

It is necessary to use reasonable care to minimize distortion and instability in fixturing calibrated artifacts used for CMM testing. The following discussion addresses sources of error due to fixturing and provides guidance for good metrology practice to minimize such effects. To the extent this guidance is followed, fixturing uncertainty should be a negligible contributor to the test uncertainty budget, so that $u(c_{\text{fix}}) \approx 0$.

Fixturing may cause deformation of a test artifact due to clamping, inertial and probing forces. The most significant effects of fixturing are bending and rocking.

Bending may cause errors for the following reasons:

a)   the parallelism error of the measuring faces increases (larger $u(c_{\text{parallel}})$, see E.2.1.4);

b)   the datums used to define the axis of the test artifact (e.g. two side faces) are deformed, and so the axis orientation and location have larger uncertainties (i.e., larger $u(p_{\text{geo}})$, see E.2.1.4);

c)   when the points probed during test measurements are not on the neutral axis of the test artifact, any bending brings them either closer to or farther from each other, depending on the offset from the neutral axis.

NOTE 9   When gauge blocks are used, error c) never occurs if ISO 3650 is followed, as the central length defined therein coincides with the neutral axis. Many step gauges are also designed to have their measuring faces on the neutral axis, or to be sufficiently rigid that bending effects are negligible.

Rocking may occur from probing forces and inertial forces (moving table CMMs only), both elastically and with hysteresis.

The following steps are recommended to reduce these effects:

—   Clamping forces should be kept to a minimum to avoid unnecessary deformation.

— Fixturing points should be chosen carefully on the test artifact, in view of its particular design, to minimize the deformation. The manufacturer's instructions should be followed whenever possible. The fixturing points are best chosen to be symmetric about the midpoint of the artifact in order to minimize the axis alignment error; the Airy points ($L/\sqrt{3}$) are often a good choice

— The design of the seats supporting the test artifact is very important in minimizing the clamping deformation. When true kinematic mountings are not practical, the clamping should be minimally over constrained.

— When the calibrated test length and the support are very different in temperature (e.g. because they have entered the room shortly before) and/or material, some settling time to allow thermal relaxation should be allowed before the final clamping .

— The support should be sufficiently rigid in the measuring direction. This includes the entire coupling chain from the test artifact to the CMM base or table, including the mounting seats, support bodies, and the means of clamping to the CMM base.

E.2.2 Bi-directional ball bars and ball plates

In a length measurement test using a calibrated ball bar or ball plate, which have been calibrated for the end-to-end length (not center-to-center length), the realized test length is the distance between two points, one on each of two spheres, along a line joining the sphere centers. This measurand is best realized using computer controlled CMMs so that the probing points are located on the (center-to-center) axis of the artifact so that the end-to-end measurement is similar to that of a gauge block. Manual CMMs generally do not have sufficient motion control to accurately touch these probing point locations. The calibrated length for a ball bar or ball plate used as a bi-directional artifact is $x_{\text{cal}} = x_{\text{center}} + r_1 + r_2$, where x_{center} = center-to-center length between the ball centers and r_1, r_2 = radii of the spheres. Usually x_{cal} is the result of a calibration for the end-to-end length but it could be the sum of the three individual calibrations, one for the center-to-center length and the two calibrated radii.

The measurement model is

$$E_{\text{L}} = (x_{\text{ind}} - e_{\text{T}} - e_\alpha) - x_{\text{cal}} + c_{\text{form1}} + c_{\text{form2}} + c_{\text{align}} + c_{\text{fix}}$$

where c_{form1} and c_{form2} are corrections for form (sphericity) errors in the two balls. Typically, for the precision balls used on ball bars and ball plates, the two form errors have the same standard uncertainty, i.e. $u(c_{\text{form1}}) = u(c_{\text{form2}}) = u(c_{\text{form}})$; see clause E.2.2.1 below.

The uncertainty components associated with errors of indication e_{T} and e_α due to tester-supplied temperature and CTE information are evaluated as in Clause E.2.1.

Using propagation of uncertainty according to the GUM gives

$$U(E_{\text{L}}) = 2u(E_{\text{L}}) = 2\sqrt{u^2(x_{\text{cal}}) + (\alpha x_{\text{cal}})^2 u^2(T) + [x_{\text{cal}}(T - 20\ °\text{C})]^2 u^2(\alpha) + 2u^2(c_{\text{form}}) + u^2(c_{\text{align}}) + u^2(c_{\text{fix}})}.$$

Test uncertainty using a ball bar or ball plate to realize a test length.

This expression is the same as that in clause E.2.1 for gauge blocks and step gauges (with the definition $x_{\text{cal}} = x_{\text{center}} + r_1 + r_2$), except for form error component $2u^2(c_{\text{form}})$. For the case where x_{cal} is the center-to-center distance plus the two ball radii, then the uncertainty of x_{cal} is the RSS of the center-to-center uncertainty and of the uncertainties of the two radii. In the more typical case where x_{cal} is the result of a end-to-end measurement the uncertainty is that of the end-to-end measurement, usually reported on associated calibration certificate.

E.2.2.1   Ball form error standard uncertainty, $u(c_{form})$
The standard uncertainty associated with the ball form error can be evaluated based on the information provided on the calibration certificate. The expanded uncertainty U reported on the certificate is converted into a standard uncertainty $u(c_{form})$ by dividing by the coverage factor k, $u(c_{form}) = U/k$; the value of k is also reported in the certificate, the most common value being $k = 2$.
The alignment and fixturing contributions to the test uncertainty when using a ball bar or ball plate are evaluated in the same manner as discussed in clauses E.2.1.4 and E.2.1.5.

E.2.3   Bi-directional laser interferometer with a gauge block
The use of a displacement measuring laser interferometer together with a gauge block is illustrated in Figure B1. The realized test length is the sum of the calibrated length x_{cal} of the gauge block and the displacement x_{laser} measured by the interferometer.

The measurement model for this type of test length is

$$E_L = (x_{ind} - e_T - e_\alpha) - (x_{cal} + x_{laser}) + c_{Abbè} + c_{align} + c_{fix}.$$

In this expression $c_{Abbè}$ is a correction for Abbe offset between the laser beam and the gauge block probing axis.

Using propagation of uncertainty according to the GUM gives

$$u(E_L) = \sqrt{u^2(x_{cal}) + (\alpha x_{cal})^2 u^2(T) + [x_{cal}(T - 20\ °C)]^2 u^2(\alpha) + u^2(x_{laser}) + u^2(c_{Abbè}) + u^2(c_{align}) + u^2(c_{fix})},$$

$$U(E_L) = 2u(E_L).$$

Test uncertainty using a laser interferometer and a gauge block to realize a test length.

The first three terms and the last two terms in the square root can be evaluated following the discussion in clause E.2.1 where x_{cal} refers to the gauge block measurement. Note that the cosine error will depend on the angle between the interferometer laser beam and the CMM motion direction.

The cosine error is usually quite small for any ordinary alignment. If a laser interferometer is aligned to within Δ in L meters of travel, the cosine error is approximately: $Error = \frac{1}{2}(\Delta/L)^2$

For 1 m of travel and 2 mm of alignment error, this gives a fractional error of 2 x 10⁻⁶, or 2 μm in one m.

The uncertainty components due to interferometer error and Abbe error are discussed below.

E.2.3.1   Laser displacement standard uncertainty, $u(x_{laser})$
A laser interferometer system measures displacement in air at temperature T, pressure P, and relative humidity RH as measured by the system 'weather station' sensors. The measured displacement x_{laser} is given by

$$x_{laser} = \frac{x_{vac}}{n},$$

where x_{vac} is the displacement that would be measured in vacuum and $n = n(P,T,RH)$ is the average index of refraction of the air along the beam path[1].

Assuming a negligible uncertainty in x_{vac} (i.e. a known laser vacuum wavelength and a perfect fringe counting system), the displacement standard uncertainty is

$$u(x_{laser}) = \frac{x_{laser}}{n} u(n).$$

Since $n \approx 1$, this becomes

$$u(x_{laser}) = x_{laser} u(n) = x_{laser} \sqrt{c_P^2 u^2(P) + c_T^2 u^2(T) + c_{RH}^2 u^2(RH)},$$

For a Helium-Neon laser in air near standard conditions, the sensitivity coefficients are given by

$$c_P = \frac{\partial n}{\partial P} = 2.7 \times 10^{-9} \ \text{Pa}^{-1},$$

$$c_T = \frac{\partial n}{\partial T} = -1 \times 10^{-6} \ \text{°C}^{-1},$$

$$c_{RH} = \frac{\partial n}{\partial RH} = -1.3 \times 10^{-8} \ \%RH^{-1}.$$

The uncertainties $u(P)$, $u(T)$ and $u(H)$ associated with the pressure, temperature and humidity measurements may be available if calibration certificates exist for the sensors. If such data is not available, these uncertainties can be assigned based on judgment, using, for example, estimates of the possible ranges of the parameter errors. For example, if one's knowledge of possible sensor errors is such that $|\Delta P| \le \Delta P_{max}$, $|\Delta T| \le \Delta T_{max}$, and $|\Delta H| \le \Delta H_{max}$, then the laser displacement uncertainty can be calculated as

$$u(x_{laser}) = x_{laser} \sqrt{c_P^2 \frac{(\Delta P_{max})^2}{3} + c_T^2 \frac{(\Delta T_{max})^2}{3} + c_H^2 \frac{(\Delta H_{max})^2}{3}}.$$

with the sensitivity coefficients given above.

E.2.3.2 Standard uncertainty component due to Abbe error, $u(c_{Abbe})$

If the line through the centers of the gauge block faces does not coincide with the interferometer (laser beam) axis, any pitch motion of the CMM ram between the positions where the gauge block faces are probed will cause an undesired error in the displacement indicated by the interferometer system. The distance between the gauge block axis and the laser beam is called an Abbe offset, and the resultant error is called an Abbe error.

For an Abbe offset z_{Abbe} and CMM ram pitch $\Delta\phi$ between the two gauge block probing points, the Abbe error is

$$c_{Abbe} = z_{Abbe} \Delta\phi.$$

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[1] The refractive index also depends on atmospheric carbon dioxide concentration, but the sensitivity to changes in CO_2 concentration is very small. The average value is about 380 µmol/mol and would have to increase by 67 µmol/mol in order to increase the refractive index by 1 part in 10^8. Potentially more significant in a shop environment are the effects of volatile organic solvents such as alcohol and acetone; if such solvents are present during CMM testing using a displacement interferometer it might be necessary to estimate their effects on the refractive index.

The Abbe offset can be measured to adequate accuracy during setup. The CMM pitch is generally unknown, so that the best estimate of $\Delta\phi$ has to be taken to be zero.

The uncertainty component due to Abbe error is

$$u(c_{Abbe}) = z_{Abbe}u(\Delta\phi),$$

where the uncertainty in z_{Abbe} has been neglected because the pitch error $\Delta\phi$ is generally a very small angle.

Abbe error and its associated uncertainty can be minimized by keeping the Abbe offset as small as possible. Unless the ram pitch error motion has been measured, its magnitude must be estimated based on experience and prior information about typical angular error motions of CMMs similar to the one being tested.

Some representative numbers suggest that the effects of Abbe error can be small, and only important for very high accuracy CMMs. With an Abbe offset $z_{Abbe} = 25$ mm and a ram pitch estimated to satisfy $|\Delta\phi|_{max} \leq 5$ arc-sec ≈ 25 µrad, the corresponding uncertainty component is

$$u(c_{Abbe}) = (25 \times 10^{-3}\ \text{mm}) \times (25 \times 10^{-6}/\sqrt{3}) \approx 0.4\ \text{µm}.$$

E.2.4 Unidirectional test lengths
A uni-directional measurement of a suitable test length may be combined with a bi-directional measurement of a gauge block in order to form a calibrated test length and then to test a CMM for length measurement errors. Several realizations of uni-directional test lengths are described in clause B.3 of Annex B and illustrated in Figure B2.

For these tests, there are two errors of indication: the indicated error E_{block} when measuring the gauge block and the indicated error E_{uni} when measuring the uni-directional test length. The total error of indication, used when deciding conformance with the MPE specification, is defined as the sum of these two errors:

$$E_{L} = E_{L,\,block} + E_{L,\,uni}.$$

The test uncertainty is then calculated, according to the GUM, as

$$U(E_{L}) = 2u(E_{L}) = 2\sqrt{u^2(E_{L,\,block}) + u^2(E_{L,\,uni})}.$$

The component $u(E_{L,\,block})$ can be evaluated following the procedure described in clause E.2.1. For a uni-directional test length realized with a calibrated uni-directional step gauge, the component $u(E_{L,\,uni})$ can be evaluated following the method used for "x_{cal}" in the discussion of E.2.1. For a uni-directional laser interferometer test length, see clause E.2.3.1.

When a uni-directional test length is realized using a calibrated ball bar or ball plate, the procedure described in clause E.2.2 must be modified slightly for the following reasons:

—   when measured in a uni-directional manner, the measurand is the center-to-center distance between the ball centers, so that the ball radii r_1 and r_2 do not appear in the analysis;

—   because the sampling strategy will in general be different than that used during calibration, there is a small correction in the measured length due to the form error of the balls.

The uni-directional test length is then given by

$$x_{uni} = x_{center} + c_{form},$$

where x_{center} is the calibrated length between the ball centers, and c_{form} is the correction for ball form error that affects the measured center-to-center length when the two spheres are measured with the sampling strategy specified in Annex B. From symmetry, the best estimate of this correction is zero.

For the point sampling strategy specified in clause B.3.3.2 and illustrated in Figure B2, a simple model of the form errors can be shown to yield, for the uncertainty component due to form error,

$$u(c_{form}) \approx 0.3F,$$

where F is the magnitude of the form error reported on the calibration certificate. In many cases the contribution of form error to the uncertainty budget will be negligible. Precision balls typically have form errors of 0.25 μm or less; two such spheres on a ball bar would result in a form error uncertainty component $u(c_{form}) = 0.3 \times 0.25 \text{ μm} = 0.075 \text{ μm}$.

Annex F
Normative
Traceability of Calibrated Test Lengths

F.1   General traceability issues in ASME B89.4.10360.2

This Report employs the interpretation of traceability described in Technical Report ASME B89.7.5 [F1]. In this Report the issue of traceability arises in conformance testing to demonstrate that the CMM meets the manufacturer's specifications. This requires the test lengths to satisfy the traceability requirements of F.2, and provides the connection back to the SI meter. Hence this allows a meaningful comparison of the measured length errors with the specified *MPE* values.

One of the traceability requirements is for "documentation traceability." This is a requirement to describe how the connection to the SI meter is achieved. For example, if a gauge block is employed to realize the test length, then the documentation traceability is the calibration certificate of the gauge block to an appropriate metrological terminus. If the test length is realized using the laser interferometer, then this interferometer must have metrological traceability to an appropriate metrological terminus (see F.3 below).

F.2   Test length traceability

Each test length required in this Report must be traceable per ASME B89.7.5. Typically, it is not necessary to document separately the traceability of each test length on a test position by test position basis, unless a different artifact is used to generate the test length. Calibrated gauge blocks, for example, might be used for the test lengths along the CMM axes and a laser interferometer used for the test lengths for the body diagonals. In such a case the traceability requirements must be met and documented for both the gauge blocks and the interferometer. Supplying the information below for each artifact employed will satisfy the traceability requirements for the test lengths. Information on evaluating the uncertainty of the test length is given in Appendix E.

1.   State the measurand: for example, the point-to-point length of a gauge block. Note: the reference length always refers to the standard temperature of 20 °C. It may be convenient, however, for measurement uncertainty considerations, to perform the calibration at a temperature other than 20 °C.

2.   Identify the measurement system or standard used: for example, a step gauge made of steel, having SN # 12345.

3.   State the expanded ($k = 2$) uncertainty associated with the test length as used at the time of measurement. Note that this includes all the uncertainty contributors prevailing at the time and conditions when the test length is measured by the CMM; details on "test uncertainty" are in Annex E.

4.   Provide an uncertainty budget describing the uncertainty components used to compute the statement of uncertainty. For a step gauge, the typical uncertainty components are the calibration uncertainty, the uncertainty in the gauge temperature (used to make the nominal thermal expansion correction) and the uncertainty in the coefficient of thermal expansion of the gauge. Additional uncertainty components may include fixturing effects; see Annex E for details.

5.   Provide documentation traceability back to an appropriate terminus of the standard used for the test length; see clause F.3 for an appropriate metrological terminus. For most artifacts a calibration certificate would suffice, assuming the certificate is from an appropriate metrological terminus.

6.   Show evidence of an internal quality assurance program so that the measurement uncertainty statement for the test length is assured. This may be a simple procedure to ensure that the test length artifact is periodically recalibrated; that other sensors, e.g., the weather station of an interferometer, are periodically recalibrated; and to ensure that the artifact fixturing or other effects are in accordance with its calibration requirements or otherwise taken into account in the uncertainty budget.

F.3   Metrological terminus

An appropriate metrological terminus for the documentation traceability is any one of the following sources; see reference [F1] for further details.

1.   A calibration report[2] from a National Measurement Institute for the test length (artifact or instrument) used as in the testing

2.   A calibration report from a competent[3] laboratory fulfilling section 5.6 of ISO 17025 [F2], or section 9 of ANSI/NCSL Z540-1, see reference [F3], for the reference length used in the testing.

3.   Documentation describing an independent realization of the SI meter[4] used to generate the reference length. This documentation will include the measurement uncertainty of the calibration and evidence that the stated uncertainty is achievable, e.g., participation in a round robin or comparison against another independently calibrated length standard.

F.4   References

[F1]   ASME B89.7.5 - 2006 *Metrological Traceability of Dimensional Measurements to the SI Unit of Length*, Technical Report, available at www.asme.org/Codes/Publications

[F2]   ISO/IEC 17025 – 2005 *General requirements for the competence of testing and calibration laboratories*, available at www.iso.org/iso/iso_catalogue.htm

[F3]   NCSL Z540-1-1994 *Calibration Laboratories and Measuring and Test Equipment – General Requirements*, available at www.ncsli.org

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

[3] A de facto means of demonstrating competence is though laboratory accreditation

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

Annex G
Normative
Decision Rule for Conformance Testing

G.1   General

The default decision rule used in ASME B89.4.10360.2 is "simple 4:1 acceptance" per ASME B89.7.3.1 [G1]. This rule requires that the expanded (k = 2) test uncertainty (see Annex E) be no greater than one-fourth the associated maximum permissible error (MPE) specification, i.e., the measurement capability index $C_m \geq 4$. In some cases, due to the state of the art or for economic reasons, it may not be practical to achieve this level of the capability index. If the C_m is less than 4, the actual value of C_m must be stated on the data sheet. Once the 4:1 uncertainty requirement is fulfilled, or the value is stated, the CMM conformance test results are acceptable if they are within the MPE specification (or are equal to the limiting value). For simple 4:1 acceptance, the acceptance zone and the zone defined by the manufacturer's MPE specification are identical. See [G1] for a complete explanation of the decision rule.

CMM users may test the CMM using their own artifacts; however, these artifacts must satisfy the C_m requirement as stated on the data sheet specified by the manufacturer and they must meet the traceability requirements of Annex F. In particular, the test uncertainty must include all components present at the time of testing; see Annex E for details.

NOTE1   The decision rule used in ASME B89.4.10360.2 is "simple 4:1 acceptance," whereas the decision rule used in the corresponding ISO Standard is "stringent acceptance with a 100% test uncertainty guardband" (see [G1] for a discussion of this terminology). This implies that any CMM that meets an ISO specification for a identical test should also pass the ASME B89.4.10360.2 test. The converse is not assured.

NOTE 2   This Report does not specify which party (the manufacturer or the user) will perform the testing or which party will pay the associated cost. Nor does this Report require that testing will be performed at the time of purchase; these contractual issues should be negotiated between the buyer and seller prior to purchase. This Report does specify the meaning of the accuracy specifications and provides a procedure to verify them. CMM manufacturers that specify this Report are expected to meet these specifications during the time period the specifications are warranted.

G.2   References

[G1]   ASME B89.7.3.1 - 2001 *Guidelines for Decision Rules: Considering Measurement Uncertainty in Determining Conformance to Specifications*, available at www.asme.org/Codes/Publications

Annex H
Informative
Interim Testing of CMM Systems

H.1 Introduction

The goal of CMM interim testing is to identify and rapidly remove from service defective CMMs before significant numbers of good parts are rejected or bad parts are accepted. The frequent application of interim testing will increase confidence in CMM performance between CMM calibrations. Interim testing is not a substitute or replacement for CMM calibration, and is not normally diagnostic in nature. Rather, it checks the validity of the calibration by detecting common CMM performance failures. It is recommended that users regularly apply interim testing to their CMMs. An effective interim test checks the CMM measurement system including subsystem components that are used in the normal operation of the CMM. This may include such components as probes, probe heads, temperature compensation systems, and rotary tables. This Annex assists CMM users by providing information on efficient interim CMM testing.

H.2 General interim testing guidelines

Limited time is available for performing interim testing, hence an efficient test must concentrate on sources of performance degradation that commonly occur. The goal is to test for as many errors as possible with a minimum number of measurements. If the test fails, additional actions are needed. These might involve further diagnostic testing or involve CMM servicing and calibration. CMM subsystem components need to be included in the interim test to broaden its scope and insure that the entire measurement system is operating correctly. Each user has special needs, so interim testing procedures and artifacts may vary from user to user; however, the following guidelines may provide some guidance.

CMM errors, whether systematic or random, reveal themselves as deviations from known lengths or as variations of several measurements of a fixed (perhaps unknown) length. The use of a known length, i.e. calibrated, artifact supplies additional useful information from the test. If a calibrated artifact is used, the uncertainty in its calibrated length should be small compared to the threshold level at which the interim test fails. Similarly, the form and surface finish of the artifact should not significantly affect the measurement.

Thermal properties of the artifact are also important for workpieces measured at a temperature other than 20 °C. In general, the user should select an artifact which has a thermal expansion coefficient that is similar to that of the workpieces commonly measured with the CMM. The uncertainty in the thermal expansion coefficient of the artifact must also be considered, as discussed in clauses 6.3 and 6.5. If the user commonly applies a correction for the thermal expansion of the workpiece, then a thermal compensation should be applied to the interim artifact. This will allow testing of the thermal compensation system as a part of the interim test procedure. Since environmental conditions may affect the performance of a CMM, it is advisable to record the temperature and other environmental parameters during an interim test, particularly if unusual conditions are present.

It is important that the artifact be dimensionally stable between interim tests, so that the measurements obtained during an interim test can be compared to those from previous interim tests and, if available, to the artifact's known length. Certain materials are dimensionally unstable and may change in length by many parts per million (µm/m) over one year. It is important that the dimensional stability (including any possible damage) of the artifact be substantially less than the smallest CMM error of significance to the user. The interim artifact should be securely located on the CMM table to prevent any possible rocking or slippage during the measurement procedure. To compare interim test results to one another, it is advisable to locate the artifact in approximately the same position and orientation for all tests. Similarly the inspection plan, such as the number of probing points taken on the artifact, should be kept constant for all tests. Widely distributing the probing points over the

gauging surface will aid in producing consistent interim testing results.

H.3 Interim testing strategies

There are several different strategies for choosing an interim artifact depending upon the application of the user. For discussion purposes, we will consider two categories: those strategies that employ an artifact which represents a typical workpiece (the artifact may be an actual workpiece from the production line) and those strategies that employ an artifact specifically designed for CMM testing. For all strategies, it is recommended that ten consecutive interim testing runs be conducted immediately after the CMM is calibrated. The mean of these ten measurements can be used to establish a baseline value for the interim artifact, and the range of values indicates the typical variation that may be expected under these conditions. Additional factors, such as thermal conditions or different operators, may further expand the range of interim testing results. If upon recalibration of a CMM, the new interim baseline measurements differ significantly from the previous baseline, then the interim artifact or the CMM calibration (or both) may be suspect and further investigation is warranted.

Some CMMs are dedicated to measurements of a single type of workpiece or a family of similar workpieces. In this situation an actual workpiece may be used as the interim testing artifact. This type of artifact will be sensitive to errors that are important to actual workpiece measurements. An additional benefit is that the user is familiar with the required workpiece measurements and consequently may have a CMM program available that can be used for the interim testing. The selected workpiece and the measured features on that workpiece should span the largest volume of the CMM work zone that is encountered during actual workpiece measurements to insure that the relevant volume of the CMM is tested. For users measuring many small workpieces located all over the CMM work zone, it is suggested that the small interim test artifact be measured at several different locations to insure that an adequate region of the work zone is tested. It is not necessary to measure every feature on the test workpiece; rather, a representative group should be selected (both for feature type and location) for the interim testing procedure. The tolerance of these selected features should be set comparable to those of the tightest tolerances found in the actual production workpieces. In general, the interim artifact should be treated, fixtured, and measured in a manner similar to that of actual workpiece to reflect the actual measurement situation. Although the use of a test workpiece as an interim artifact has merit, it is important to note that the testing results are valid only for workpieces of a similar design and may not indicate the errors present when measuring a workpiece significantly different from the test artifact.

An artifact specifically designed for interim testing should be sensitive to common CMM errors. CMM angular geometry errors typically increase in magnitude in direct proportion to the length of the artifact. For example, a squareness error of 10 arc-seconds can produce an error of 5 μm over a distance of 0.1 meter, but it becomes an error of 50 μm over 1.0 meter. This illustrates a useful principle: to increase the sensitivity to angular errors, measure long artifacts. Ideally, the artifact should be as long as practical; typically the longest calibrated test length used in the E_0 test is employed. On artifacts that produce several lengths upon measurement, e.g., ball plates, the longest length present will provide the greatest sensitivity to angular errors. (A short artifact positioned in several locations in the CMM work zone is not equivalent and will not have the same sensitivity to angular errors as a long artifact.) The orientation and position of the artifact is also important. Certain artifact orientations can maximize the effect of geometry errors and hence allow them to be detected. As an example, consider the pure squareness error shown in Figure H1. It is apparent that the measured length of the artifact in the square coordinate system (X1, Y1) is longer than that of the out-of-square system (X2, Y2). If the artifact is a known length, then this discrepancy appears as a measurement error. Even if the artifact length is unknown, this property can be exploited by measuring the same artifact in two "crossed" orientations as shown in Figure H2. By this technique, the angular deviation from squareness (shown as α in Figure H2) can be determined in the absence of other errors. In three dimensions, the analogous situation is carried out by reorienting the artifact along all four of the body diagonals of the work zone as seen in Figure H3. This procedure can be conducted with many different artifacts such as a ball bar, a step gauge, or a long gauge block. Alternatively, the use of

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calibrated ball or hole plates may allow more than one such body diagonal to be measured in each orientation.

An artifact specifically designed for interim testing should provide assurance that the entire measurement system is performing correctly. If only four body diagonal positions are tested, the artifact should be calibrated in order to test the accuracy of the scale on each CMM axis. (If the artifact is of unknown length, then measurements in additional positions can identify relative errors between the scales, but at least one known length is required to establish the true accuracy of the scales.)

The CMM probe should be checked to ensure it is in good working order. This may involve an explicit probe test which checks the directional sensitivity of the probe, i.e., probe lobing (such as described in ASME B89.4.10360.5) or may be incorporated into part of the general CMM geometry test such as measuring a long gauge block which is oriented in several different directions. Similarly, to test the probe qualification, which involves the accuracy of the CMM probe qualification artifact (typically a sphere with a calibrated diameter) a true bi-directional measurement of a known length is required. This might be the length of a gage block or the diameter of a ring gage or of a precision sphere. It is important to note that the measurement of a uni-directional step gage or the center-to-center distance between spheres of a ball bar does not check the probe qualification. If multiple styli are used (either with a stylus cluster, e.g., "star probe", or with an indexable probe head), then a test should be included which checks the ability to locate one stylus ball relative to another. Such a test would include multiple styli used in a single measurement (e.g., ASME B89.4.10360.5). If a probe changing rack is available, then this subsystem should be tested by swapping probes in and out of the rack. This not only checks the repeatability with probe changing effects included, but defective probes in the rack may also be discovered. For CMMs which include a rotary table, an appropriate test such as the DCC rotary axis test (ASME B89.4.10360.3) should be included as part of the interim testing procedure. In summary, an effective interim test artifact should examine the complete CMM measurement system to assure confidence in the entire measurement process.

H.4 Interim testing example

The details of an interim test are highly user dependent, since users have different types of CMMs, different accuracy requirements, measure different types of workpieces made of different materials, and their operators and facilities are different. Given the short time to carry out the interim test, different users will optimize the interim test in different ways to suit their needs. The following example is for a vertical ram CMM with a nearly cubic (1x1x1) work zone having an indexable probe head, a probe changing rack containing two additional probes, and a temperature compensation system. This specific example is given to provide general guidance to CMM users; the actual CMM system may require different or further tests. Additionally, some users may desire more extensive testing or employ alternative strategies from the procedures listed below.

As an example of a specific interim test, the user chooses a ball bar calibrated for ball roundness, ball size, and center-to-center distance. The ball bar temperature is measured in each position using the part temperature sensor, and the appropriate thermal correction is applied to all test results. A basic test involves measuring the four body diagonals of the CMM. In each position, the user decides to take eight points on each ball of the ball bar. The user determines the apparent form error of the ball, the difference between the least squares sphere diameter and the calibrated diameter, and the differences between the measured ball bar (center-to-center) lengths and the calibrated value. These results are plotted and shown in Figure H4.
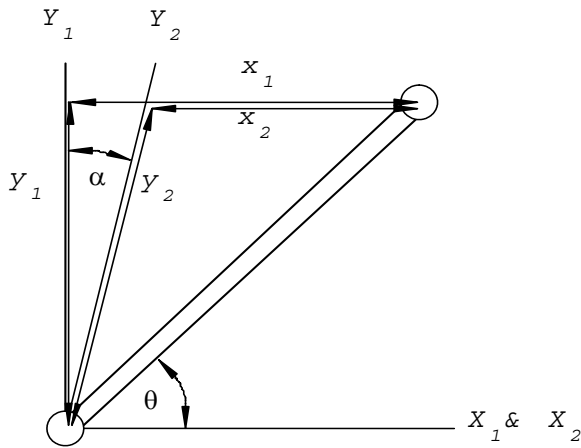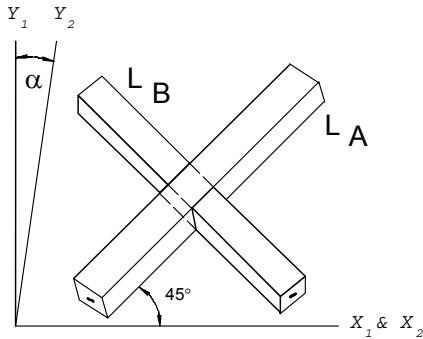
$$L_1 = \sqrt{x_1^2 + y_1^2} \quad L_2 = \sqrt{x_2^2 + y_2^2}$$

$$\alpha = \frac{L_1 - L_2}{L_1 \, Cos\theta \, Sin\theta}$$

Figure H1

L_1 is the true length of the ball bar as measured in a square coordinate system; L_2 is the (apparently foreshortened) length as measured in an out-of-square coordinate system. Note $L_1 > L_2$.

$$\alpha = \frac{2(L_A - L_B)}{L_A + L_B} \quad \text{radians}$$

Figure H2 XY squareness (in the absence of other errors) can be estimated using the same artifact measured in two crossed positions at approximately 45° and 135°.
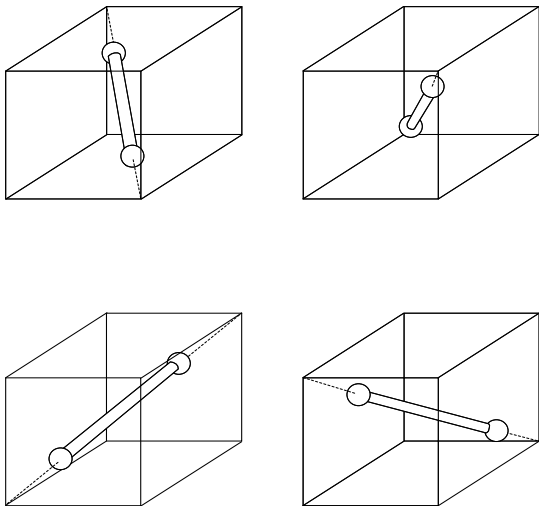

Figure H3 Ball bar indexed through the body diagonals of the CMM work zone. These positions are sensitive to squareness errors of all three axes .

In the first body diagonal position, the user employs a single probe (oriented along the ram axis). In this position, the measured form error of the balls shows the repeatability of the CMM and the probe, and any probe lobing effects. The ball diameter measurements check the probe qualification, i.e., stylus ball size, and the short range scale errors. The bar (center-to-center) length measurement checks for long range (CMM geometry or thermal expansion) errors in that orientation. For the second body diagonal, a similar measurement is conducted but with the probe head indexed so that the probe is perpendicular to the ram axis. This measurement will produce similar information to that of the first body diagonal position but will include any Z axis roll error in the CMM geometry. In the third body diagonal position, each ball of the ball bar is measured with the probe head indexed in several positions; this will supply information on probe head repeatability and the ability to accurately find a stylus ball location relative to others with different probe head orientations. The final body diagonal position checks for any defective probes present in the probe rack and the rack's probe changing ability. The first ball of the ball bar in this position is measured using the second probe obtained from the probe-changing rack, and the second ball of the ball bar is measured with the final (#3) probe from the probe rack. The form error and diameter reported for each ball of the ball bar test each of the two probes for probe lobing effects and stylus size qualification, respectively. (If additional probes are available, these could be checked by measuring each ball of the ball bar, in each ball bar position, with a different probe.)

Figure H5 shows one possible method of data analysis of the interim test. For each interim test all four center-to-center length deviations, all eight ball diameters, and the eight measured sphere form errors are plotted. The test is passed if all these measurements are within the threshold value limits. Some users may prefer a single plot representing the test results (instead of the three shown in Figures H4 and H5). Such a plot can easily be constructed, as shown in Figure H6, by combining the largest length deviation, the largest diameter deviation, and one half the largest form deviation, in a root sum of squares (RSS) manner. (One-half the largest form deviation is used so each of the three contributions is appropriately weighted). This method has the advantage of displaying only a single graph but provides less information as to the sources of error. (If a CMM problem does develop, plots such as those in Figure H5 could be constructed displaying all the data from the previous test results.)

There are many different methods a user can choose to establish testing thresholds. These include using the manufacturer's stated CMM performance values for the particular CMM under consideration. This might involve specifications from the ASME B89.4.10360.X or other appropriate national or international standards. Other methods to determine the thresholds include examining the tightest tolerance of a feature found on the user's workpiece and reducing this by an appropriate ratio. To avoid false alarms, the threshold levels should exceed all variations arising from normal operations. This may include such factors as different operators and different thermal conditions, e.g., time of day or week.
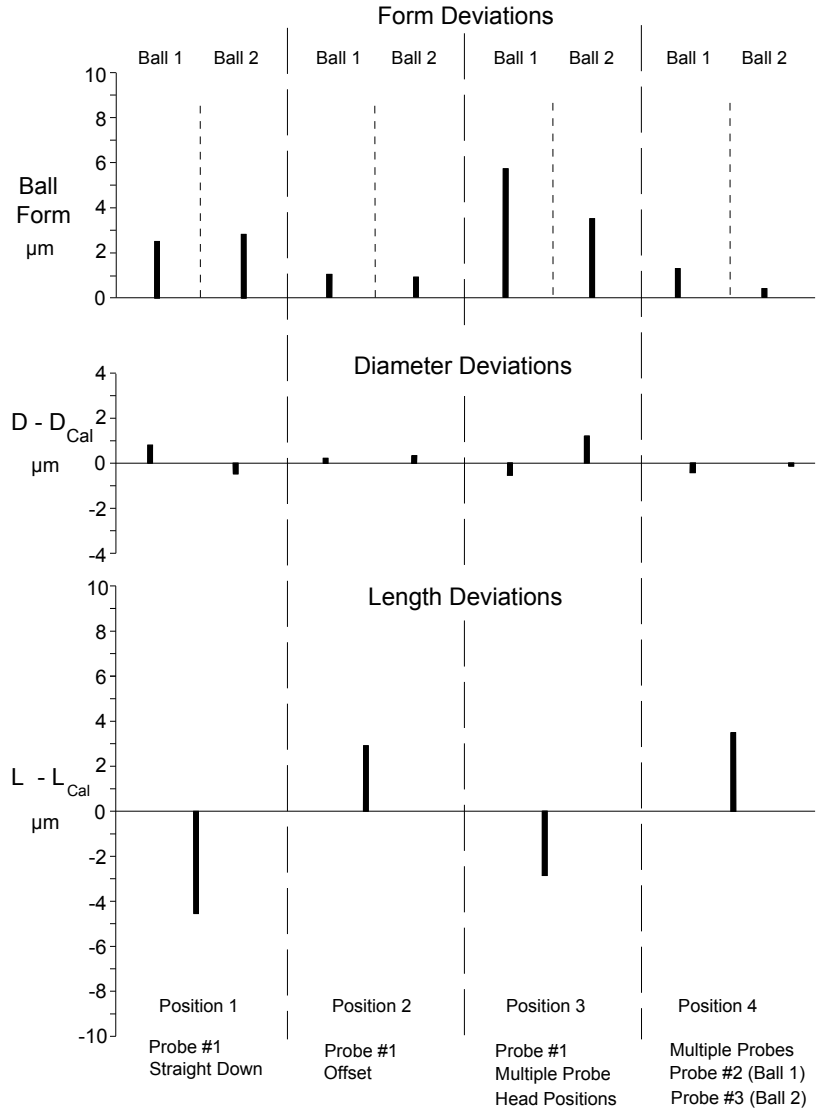
Figure H4   Results of an interim test using one ball bar in four (body diagonal) positions. The test includes checking the temperature compensation system, the indexable probe head, and the three different probes available in a probe-changing rack.

H.5 Testing frequency

The frequency of interim testing is highly user dependent. A CMM being operated three shifts a day with multiple operators in a harsh environment is likely to experience many more problems than the same machine being used one shift a day by a single operator in an excellent 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 CMM operating hours. Some users with high value and/or safety critical workpieces may elect to perform daily tests, where other users might test weekly or monthly. Additionally, interim testing should be conducted after any sort of significant event such as a CMM collision, replacement of a subsystem component, or the occurrence of abnormal temperature variations or gradients.
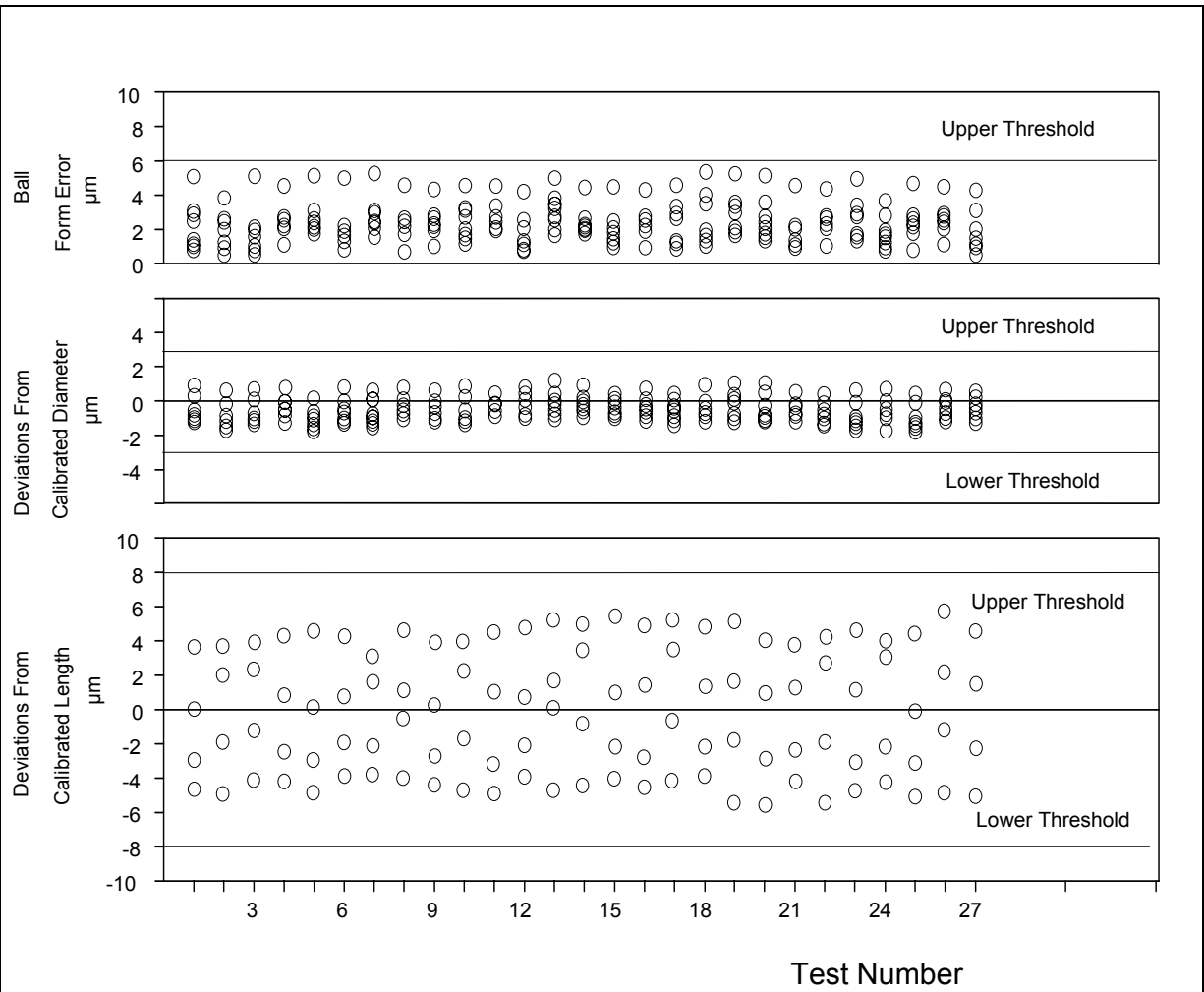
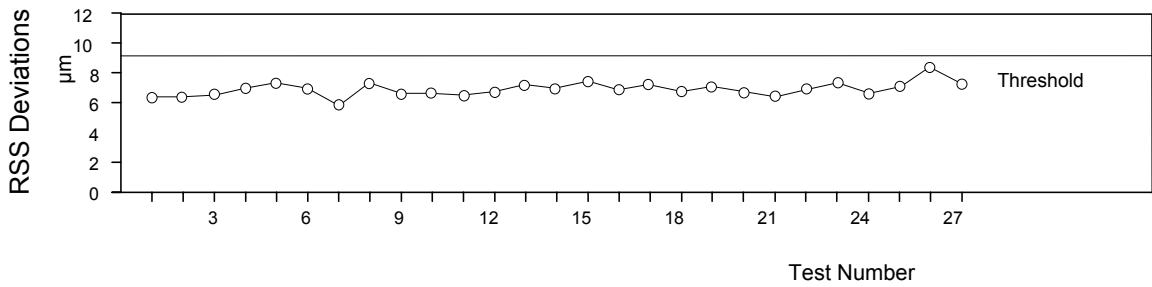**Figure H5 Summary plots of several interim test results**

Figure H6 Summary plot of combined interim testing results

H.6 Large CMMs

CMMs with large work zones that are approximately cubic (1x1x1) should follow H.1-H.4 with the following supplementary information. (For large CMMs, approximately cubic work zones can include all cases where the ratio of the work zone's longest to shortest axis is less than 2.) H.1-H.4 recommends that a general purpose interim testing artifact should have its length be at least 75% of the shortest axis of a CMM with a nearly cubic work zone. This condition may be difficult to fulfill with large CMMs as the artifacts may become unwieldy, expensive, and difficult to calibrate. Furthermore, large interim testing artifacts may require special fixturing to avoid distortions caused by gravity or the probing force of the CMMs. Since these distortions often increase as the cube of the artifact's length, acceptably small distortions on short artifacts can rapidly become significant error sources as the length of the artifact increases. Consequently, fixturing that minimizes these effects is highly recommended. Finally, thermal effects are especially important on large artifacts. The magnitude of these errors can be estimated by the Nominal Differential Expansion (NDE), and the uncertainty in the NDE, i.e. the UNDE. The following recommendations provide alternative ways of overcoming the testing difficulties of large CMMs.

Sub-Work zones: Since some large CMMs use a significant fraction of their work zone for part mounting, a smaller work zone (or a series of smaller work zones) might be used for the actual measurements. In these cases the testing artifact may comply with the recommendation of using a length equal to 75% of the shortest axis of the sub-work zone. An example of such a situation would be a CMM which inspects physically large parts that need to fit into the work zone but with the actual measurement region on the part being a small sub-volume of the part's physical size. Accordingly, a 0.9 m ball bar can easily be used to test a measurement work zone having a 1.2 m length side. Similarly, artifacts of length 1.5 m can be used to test measurements work zones having a shortest axis of up to 2 m. Artifacts greater than 1.5 m become increasingly problematic, and hence, this represents the limit of practically implementing this approach.

Artifact Staging: For very large CMMs, with the shortest work zone axis greater than 2 m, large physical artifacts may become impractical. In this situation a reasonably large artifact (e.g. 0.9 – 1.5 m) can be staged in the work zone. The staging should cover a distance of at least 75% of the shortest axis of the work zone. It is not recommended to stage the artifact more than three times, since the artifact's length relative to the work zone size is small in this situation, hence losing sensitivity to angular errors in addition to becoming very time consuming. Using this strategy with a 1.5 m artifact allows testing of a cubic work zone CMM with an axis of up to 6 m.

Testing with Optical Systems: For CMM work zones with a shortest axis of more than 2 m, the use of an optical displacement measuring system, e.g. a laser interferometer, may be desirable. If optical measurements are taken in nonstandard environmental conditions, then the wavelength considerations of Annex E are recommended. Additionally, long beam paths may have spatial gradients present; this effect should be assessed and reduced, e.g. by air mixing with fans, if necessary. The use of an optical system can employ the same procedure recommended for physical artifacts, i.e., the measurement of body diagonals, with at least one length being recorded for every 2 m of displacement traveled. For example, a CMM with a 4 m x 5 m x 6 m work zone could be tested along the body diagonal with at least 3 m of distance checked (75% of 4 m), and with at least one intermediate point recorded. Since for most optical systems the measurement time is a small fraction of the setup time, adding additional measurement points is advisable, e.g., in the above situation a measurement of the body diagonal lines of 7 m with the points spaced at 1 m intervals would be desirable. For large CMMs that are not vector driven, i.e., can not operate all three axes simultaneously, it may be impossible to maintain the necessary optical alignment required by the laser interferometer. For these CMMs an optical tracking system, e.g., laser tracker, can maintain the optical alignment as the body diagonals are traversed and may be used.

Care must be exercised to ensure that the optical measurement system has a sufficiently low uncertainty relative to the CMM under test. If it becomes necessary to move the beamsplitter / remote interferometer rather than the retroreflector when making length measurements, problems can arise if the beamsplitter is imperfectly made and bends the transmitted light slightly. Under these circumstances it is never possible to obtain good alignment of the beam with the direction of motion; if the laser beam exiting the beamsplitter is well aligned with the direction of motion, then the incoming beam will be misaligned and will walk across the face of the beamsplitter as the beamsplitter is translated. Thus a potential for both signal loss and misalignment errors exists when translating the beamsplitter. The problem is easily avoided by using a good quality optic that does not bend the transmitted light. Additionally, the correction for environmental effects on the wavelength of light over the measured distance should be considered as a potential error source (see Annex E). Similarly, the use of optical coordinate systems, e.g., laser trackers, must have a sufficiently small system uncertainty relative to the CMM under test.

Since most optical systems used for interim testing do not involve the CMM probe or related subsystems, additional tests are needed to check these systems. The use of a test sphere, calibrated for form and diameter, can be employed to check the CMM probe, indexable probe head, and CMM probe/stylus changing systems. For example, if all of the above subsystems are available, then a simple test would be to measure a calibrated sphere with a set of points taken using a combination of different probes/styli (accessed through probe/stylus changing) and different probe head index positions. This collection of points is (least squares) fit to a sphere and the resulting form and diameter errors examined. The sphere's diameter error is a bi-directional length test and checks the probe's qualification for features of size, whereas the form error checks the probe lobing of the different probes (see ASME B89.4.10360.5) and the index positions relative to each other. Additionally, if the CMM has a part temperature compensation system, also known as an Automated Nominal Differential Expansion (ANDE) compensation system, this will not be tested during the optical measurement and should be checked independently, for example, by measuring a reasonably long calibrated artifact having a nonzero expansion coefficient. During this measurement, the temperature of the artifact should be measured with the CMM part sensor and used for the ANDE correction. Deviations between the thermally compensated measured value and the calibrated value for the artifact length may indicate problems with the compensation system.

H.7 CMMS used in the duplex mode
For CMMs used in the duplex mode the procedures described in this Annex can be used with at least some of the artifact measurements taken under the duplex condition. This is achieved by measuring opposite ends of the test artifact (ball bar, step gauge, gauge block, etc.) with different arms of the CMM. Similarly, if a ball plate (or hole plate) artifact is employed, then approximately half of the balls (holes) may be measured with each arm. If the CMM is rarely used in the duplex mode, then each arm may be interim tested independently, and a few additional duplex measurements included. For very large CMMs used in the duplex mode the use of a laser interferometer (or similar optical system) is recommended. In this case, the retroreflector is mounted in the ram of one arm and the interferometer is mounted in the ram of the second arm. (See the precautions above regarding testing with optical systems.) The distance between the two CMM arms is varied along a common direction determined by the laser beam path. If such an optical procedure is used, then the testing of the subsystems (e.g. probe head) is also needed, as described in H.6.

H.8 High aspect ratio CMMs
CMMs having work zones with the ratio between the longest to shortest axes (the aspect ratio) greater than 2 may require modified testing procedures. For CMMs with aspect ratios of $\leq$ 3 and having body diagonals less than 4 m long, interim testing can be performed using an artifact at least one third the length of the body diagonal. For example, a CMM with axes of 0.5 m x 1 m x 1.5 m has a body diagonal 2 m long, thus a minimal length testing artifact would be 0.7 m. CMMs with aspect ratios greater than 3 are usually designed for a special purpose, for example, measuring the

straightness of a long narrow part. In this case a special purpose test which is designed around the measurement requirement may be appropriate. In the above example, the use of a straightness interferometer together with subsystem (e.g., probe) tests may be sufficient for the measurement application. In other situations, the use of two ball bars may be sufficient to check the CMM. For example, one long bar could be oriented along some combination of body diagonals, long face diagonals, and the long axis of the CMM. A second shorter bar could be oriented along some combination of the short face diagonals and the short axis of the CMM.

H.9 Rotary table CMMs

CMMs having a rotary table can be tested by an abbreviated form of the test described in ASME B89.4.10360.3. In cases where the measurement volume of interest is approximately that of the rotary table, then the two ball setup is used with a minimum of four angular positions selected from Table 2 of ASME B89.4.10360.3, is sufficient to check the CMM. In situations where the measurement volume is substantially larger than that accessible to the rotary table then additional measurements using a method previously described, e.g., measuring a fixed length artifact, are recommended. Note that part loading effects can significantly affect the four-axis errors.

Annex I   ASME B89.4.10360.2 Data sheet
Normative

Machine Model[1] _____

System Description

CMM type[2]	
Probing system[3, 4]	
Stylus system[3, 4]	
Basic software[3, 4]	
Articulation system[3, 4]	
Modes of operation[5]	
Overall CMM dimensions	mm
Measuring volume (X, Y, Z)	mm
Mass of CMM	kg
Resolution (linear axes)	μm
Electrical description[6]	

Mandatory Performance Specifications[7]

$E_{0, MPE}$	μm
$E_{150, MPE}$	μm
$R_{0, MPL}$	μm

Optional Performance Specifications

$E_{0X, MPE}$	μm
$E_{0Y, MPE}$	μm
$E_{0Z, MPE}$	μm
$R_{Pt, MPL}$	μm

Rated Conditions

T_{S_MIN}:	°C	ΔT_{S_1}:	°C / hour	ΔT_{S_H}:	°C /m
T_{S_MAX}:	°C	ΔT_{S_24}:	°C / day	ΔT_{S_V}:	°C /m
CTE of calibrated test length[7] – upper limit:			$\times 10^{-6}$ / °C	lower limit (optional):	$\times 10^{-6}$ / °C
Uncertainty of CTE of calibrated test length (k = 2)– upper limit:					$\times 10^{-6}$ / °C
C_m for length tests: _____		If $1 \le C_m < 4$ Check ☐ "Low C_m"			
Effective CTE of each machine scale[8]:					$\times 10^{-6}$ / °C
Maximum air supply pressure:					Pa
Electrical supply:					
Maximum load on table:	kg	Maximum floor vibration:			m/s² f(Hz)

Limiting Conditions

Ambient temperature:	°C
Ambient relative humidity:	%
Maximum air supply pressure:	Pa
Electrical supply[9]:	
Maximum load on table:	kg
Maximum load on table per unit area:	kg/m²
Maximum point load on table per unit area:	kg/cm²
Maximum floor loading per CMM supporting foot:	kg
Probe overtravel:	mm

[1]Manufacturers unique identifier, e.g. brand name and model

[2] e.g., moving bridge, etc.

[3]As used in testing to meet performance specifications. If articulation system is specified, then E_{150} will be tested using the articulating system; otherwise an offset stylus will be used.

[4]Manufacturers description/version number

[5]Non-motorized with manual operator control, motorized with operator control, e.g., via joysticks, or motorized with programmed control

[6]Amperes, voltage range, single phase of three phase or three phase and neutral

[7]MPE and MPL values must be marked with an asterisk (*) if a non-normal CTE calibrated test length is used. In such case an artifact description is needed as described in 6.3.2.

[8]Applies only to machines without temperature compensation

[9] Includes voltage and amperage requirements and power dissipation of the CMM and accessories

Annex J
Figures 12, 13 and 14 from ISO 10360-1:2000

Informative

The following are figures 12, 13 and 14 of ISO 10360-1:2000. The captions have been modified to reflect the notation used in this Report. The symbol L in these figures represents the length of the calibrated test length.
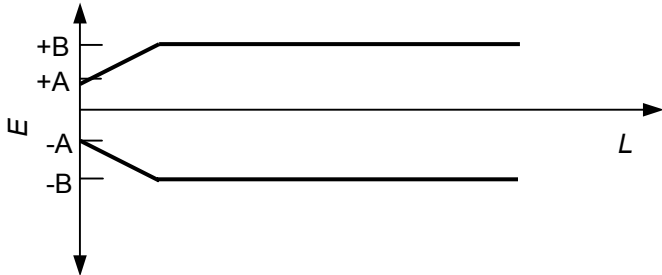
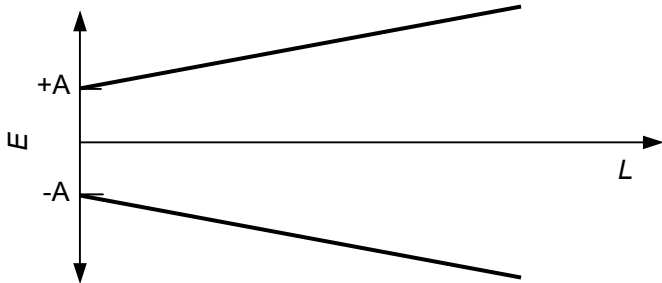Figure 12   Maximum permissible error of indication for $E_{0, MPE}$ and $E_{150, MPE}$.

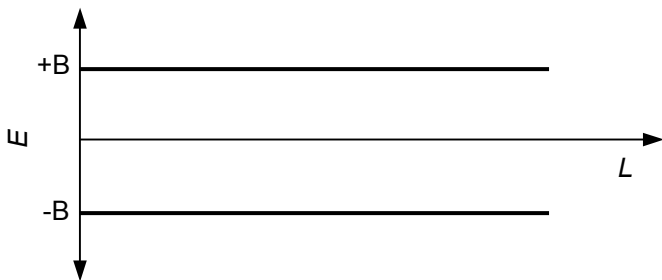Figure 13   Maximum permissible error of indication for $E_{0, MPE}$ and $E_{150, MPE}$.

Figure 14   Maximum permissible error of indication for $E_{0, MPE}$ and $E_{150, MPE}$.

The figures above are also used for $R_{0, MPL}$ and $R_{Pt, MPL}$. In these cases, the negative (bottom) half of the graph is not applicable, since any R_0 or R_{Pt} value can never be less than zero.

Bibliography

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

[2]   ISO 10360-3, *Geometrical product specifications (GPS) — Acceptance and reverification test for coordinate measuring machines (CMM) — Part 3: CMMs with the axis of a rotary table as the fourth axis*

[3]   ISO 10360-4, *Geometrical product specifications (GPS) — Acceptance and reverification test for coordinate measuring machines (CMM) — Part 4: CMMs used in scanning measuring mode*

[4]   ISO 10360-5:2000, *Geometrical product specifications (GPS) — Acceptance and reverification test for coordinate measuring machines (CMM) — Part 5: CMMs using multiple-stylus probing systems*

[5]   ISO/TR 14638, *Geometrical Product Specifications (GPS) — Masterplan*

[6]   ISO/TS 15530 series, *Geometrical product specifications (GPS) — Coordinate measuring machines (CMM): Technique for determining the uncertainty of measurement*

[7]   ISO/TR 16015, *Geometrical product specifications (GPS) - Systematic errors and contributions to measurement uncertainty of length measurement due to thermal influences*

[8]   ISO/PAS, *General product specifications (GPS) – Coordinate measuring machines (CMM): Testing the performance of CMMs using single stylus contacting probing systems*

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