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Geometrical product specifications (GPS) — Guidelines for the evaluation of coordinate measuring machine (CMM) test uncertainty

Spécification géométrique des produits (GPS) — Lignes directrices pour l'estimation de l'incertitude d'essai des machines à mesurer tridimensionnelles (MMT)

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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.

In other circumstances, particularly when there is an urgent market requirement for such documents, a technical committee may decide to publish other types of normative document:

— an ISO Publicly Available Specification (ISO/PAS) represents an agreement between technical experts in an ISO working group and is accepted for publication if it is approved by more than 50 % of the members of the parent committee casting a vote;

— an ISO Technical Specification (ISO/TS) represents an agreement between the members of a technical committee and is accepted for publication if it is approved by 2/3 of the members of the committee casting a vote.

An ISO/PAS or ISO/TS is reviewed after three years in order to decide whether it will be confirmed for a further three years, revised to become an International Standard, or withdrawn. If the ISO/PAS or ISO/TS is confirmed, it is reviewed again after a further three years, at which time it must either be transformed into an International Standard or be withdrawn.

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/TS 23165 was prepared by Technical Committee ISO/TC 213, *Dimensional and geometrical product specifications and verification*.

Introduction

This Technical Specification belongs to the general Geometrical product specification (GPS) series of documents (see ISO/TR 14638). It influences chain link 5 of the chains of standards on size, distance, radius, angle, form, orientation, location, run-out and datums in the general GPS matrix.

For more detailed information about the relationship of this Technical Specification to other standards and to the GPS matrix model, see Annex D.

ISO 10360-2 deals with the application of the ISO 14253-1 decision rule, which proves conformance or non-conformance of a coordinate measuring machine (CMM) that is accepted or re-verified with its specification. In turn, this decision rule is based on a statement of the measurement uncertainty incurred while testing, and hence requires a full evaluation of the test uncertainty. This uncertainty expresses how accurate the test is, and hence how narrow the safety margins need to be set in order to make a rational decision at a specified confidence level.

Usual practice in CMM measurement familiarizes metrologists and practitioners with measurement uncertainty. Any possible effect which may affect the measurement result is considered and quantified as an uncertainty contributor, and eventually summed up to achieve the combined uncertainty. The purpose of the measurement is to gather quantitative information on a given measurand, and the uncertainty statement expresses how reliable that information is.

In the case of a performance test of a CMM, the purpose of the measurement is to investigate the CMM's performance rather than the form or size of a material standard, which is calibrated and therefore well-known in advance. The uncertainty being evaluated in this case quantifies how accurate the test is. The test detects the quality of the CMM by comparing the measurement test values with the known calibrated values of the material standards of size (probing error, P, or error of indication, E), and not through the uncertainty statement.

Consequently, only those uncertainty components that pertain to the test itself are included in the test uncertainty budget as contributors. In particular, instrumental errors introduced by the CMM are not included in the budget. In total, they constitute the probing error, P, or the error of indication, E, but do not compromise the test reliability and hence are not contributors to the test uncertainty.

From a different viewpoint, the ISO 14253-1 principle is that it is always the person performing the measurement who is liable for the uncertainty, whether in proving conformance or non-conformance. In other words, the tester is responsible for any imperfection which may occur during the test, and he takes this into account in terms of test uncertainty. A corollary of this is that the tester should only be held accountable for the elements under his responsibility, i.e. only these elements should be included in the test uncertainty budget. As the ISO 10360-2 test is not necessarily performed by the CMM manufacturer, the tester does not have any responsibility for the CMM instrumental errors. For example, a purchaser may want to prove that a CMM with large errors falls outside specification; if the CMM errors were to be considered in the budget, the resulting test uncertainty would be so large that it probably could not prove anything at all. When the test is performed by a CMM manufacturer, the latter, as the tester, takes responsibility for any imperfection in the test implementation with the test uncertainty — which narrows the acceptance zone —, and, as the manufacturer, takes responsibility for any imperfection of the CMM regarding any large values of the probing error, P, and error of indication, E.

Geometrical product specifications (GPS) — Guidelines for the evaluation of coordinate measuring machine (CMM) test uncertainty

1 Scope

This Technical Specification gives guidance for the application of the test described in ISO 10360-2, by explaining the evaluation of the test uncertainty required for ISO 14253-1.

2 Normative references

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

ISO 1:2002, *Geometrical Product Specifications (GPS) — Standard reference temperature for geometrical product specification and verification*

ISO 3650:1998, *Geometrical Product Specifications (GPS) — Length standards — Gauge blocks*

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

ISO 10360-2:2001, *Geometrical Product Specifications (GPS) — Acceptance and reverification tests for coordinate measuring machines (CMM) — Part 2: CMMs used for measuring size*

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/TS 14253-2:1999, *Geometrical Product Specifications (GPS) — Inspection by measurement of workpieces and measuring equipment — Part 2: Guide to the estimation of uncertainty in GPS measurement, in calibration of measuring equipment and in product verification*

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

ISO/TS 17450-2:2002, *Geometrical product specifications (GPS) — General concepts — Part 2: Basic tenets, specifications, operators and uncertainties*

International vocabulary of basic and general terms in metrology (VIM), BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML, 2nd ed., 1993

Guide to the expression of uncertainty in measurement (GUM), BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML, 1993, corrected and reprinted in 1995

3 Terms and definitions

For the purpose of this Technical Specification, the definitions given in ISO 10360-1, ISO 14660-1, ISO 14253-1, ISO/TS 17450-2, VIM and the following apply.

3.1
test uncertainty
expanded uncertainty, U, associated solely with the testing equipment and its use in the test, which modifies the conformance and non-conformance zones, in accordance with the decision rule in ISO 14253-1

NOTE 1 Test uncertainty is a measure of the quality of the testing equipment and its use in the test. It is not a measure of CMM performance, which is determined from probing error, P, and error of indication for size measurement, E.

NOTE 2 Test uncertainty is controlled by and is the responsibility of the tester, who provides and uses the test equipment and suffers a reduced conformance or non-conformance zone in the case of a large test uncertainty.

3.2
tester
party who performs the test defined in the ISO 10360-2

NOTE 1 In an acceptance test, the tester can be either the supplier or the customer, possibly represented by a third party.

NOTE 2 In a reverification test, the tester is the user, possibly represented by a third party.

NOTE 3 The tester is always responsible for the test uncertainty.

3.3
tester counterpart
party other than the tester

NOTE 1 In an acceptance test, the tester counterpart can be either the customer or the supplier, possibly represented by a third party.

NOTE 2 In a reverification test, the tester counterpart is the user himself, possibly represented by a third party.

3.4
coefficient of thermal expansion
CTE
⟨material standard of size⟩ coefficient of thermal expansion of a material at 20 °C

NOTE For the purpose of this Technical Specification, only the CTE of the material standard of size is considered.

4 General

This Technical Specification provides simplified equations for the test uncertainty of the quantities tested in accordance with ISO 10360-2 (i.e. the probing error, P, and the error of indication, E), and is intended as a quick reference for application. More detailed information is given in Annex A, which provides the general error models from which the simplified equations are derived, as well as some discussion of the nature of each uncertainty component, guidance on how to keep it to a minimum, and how to estimate its input uncertainty. In addition, possible uncertainty contributors are listed. Even if the main body alone may suffice for day-to-day use, a careful reading of Annex A is recommended for background information, as well as for typical applications.

The simplified equations for test uncertainty, which are given in this Technical Specification for the main uncertainty contributors, are representative in most common circumstances. They are, however, limited to these circumstances and may be inadequate in a particular case. A careful analysis of the actual circumstances is recommended in order to ascertain whether a given contributor listed in Annex A is in fact negligible, or not.

Once the combined standard uncertainties $u(P)$ or $u(E)$ are evaluated in accordance with the simplified equations, the expanded uncertainty $U(P)$ or $U(E)$ are obtained through multiplication by a coverage factor, k, as follows:

$$U(P) = k \times u(P) \tag{1}$$

and

$$U(E) = k \times u(E) \tag{2}$$

The value $k = 2$ shall be used.

Annex B deals with the special case when the material standard of size is offered by the tester counterpart.

Fully developed numerical examples are given in Annex C.

5 Test probing error

The recommended equation for the standard uncertainty of the probing error, $u(P)$, is

$$u(P) = \sqrt{\left(\frac{F}{2}\right)^2 + u^2(F)} \tag{3}$$

where

F is the form error reported in the calibration certificate

$u(F)$ is the standard uncertainty of the form error stated in the calibration certificate

The expanded uncertainty, U, reported in the certificate shall be transformed into the standard uncertainty, u, by dividing by the coverage factor, k, $u = U/k$. The value of k is also reported in the certificate, the most common value being $k = 2$.

NOTE Insufficient rigidity of the test sphere can cause additional errors in the value of P, which are not accounted for in the uncertainty equation above (see A.2.2 for details).

6 Test of size

6.1 General

The recommended equation for the standard uncertainty of the error of indication, $u(E)$, is

$$u(E) = \sqrt{u^2(\varepsilon_{\text{cal}}) + u^2(\varepsilon_\alpha) + u^2(\varepsilon_t) + u^2(\varepsilon_{\text{align}}) + u^2(\varepsilon_{\text{fixt}})} \tag{4}$$

where

ε_{cal} is the calibration error of the material standard of size;

ε_α is the error due to the input value of the CTE of the material standard of size;

ε_t is the error due to the input value of the temperature of the material standard of size;

$\varepsilon_{\text{align}}$ is the error due to misalignment of the material standard of size;

$\varepsilon_{\text{fixt}}$ is the error due to fixturing the material standard of size.

6.2 Analysis of the uncertainty contributors

6.2.1 Uncertainty due to the calibration of the material standards of size, $u(\varepsilon_{cal})$

The recommended equation for this uncertainty component is

$$u\left(\varepsilon_{cal}\right) = \frac{U_{cal}}{k} \tag{5}$$

where

U_{cal} is the expanded calibration uncertainty of the material standard of size reported in the calibration certificate;

k is the coverage factor of U_{cal}, reported in the calibration certificate.

NOTE A typical value of the coverage factor is $k = 2$.

6.2.2 Uncertainty due to the CTE of the material standard of size, $u(\varepsilon_\alpha)$

This uncertainty component should be considered only when the CMM requires the tester to input a CTE value. Hence, it should be discarded for thermally-uncompensated CMMs, i.e. the value $u(\varepsilon_\alpha) = 0$ should be used in Equation 4.

The recommended equation for this uncertainty component is

$$u(\varepsilon_\alpha) = L \times (|t - 20\ °\text{C}|) \times u(\alpha) \tag{6}$$

where

L is the size of the material standard being measured;

t is the temperature of the material standard of size, when measured;

20 °C is the reference temperature (see ISO 1);

$u(\alpha)$ is the standard uncertainty of the CTE of the material standard of size.

The value of t in Equation 6 should be measured or estimated for each test position.

To evaluate the input uncertainty $u(\alpha)$, the following procedures are suggested.

- If the material standard of size has been calibrated for its CTE, the uncertainty reported in the calibration certificate should be taken. The expanded uncertainty, U, reported in the certificate shall be transformed into the standard uncertainty, u, by dividing by the coverage factor k, $u = U/k$. The value of k is also reported in the certificate, the most common value being $k = 2$.
- If the CTE of the standard has not been calibrated, technical literature may report typical ranges of values for the material of the standard of size. If so, the span, T_α, should be divided by the square root of 12, $u\left(\alpha\right) = T_\alpha \big/ \sqrt{12}$.
- In the particular case of steel gauge blocks, ISO 3650 specifies a range $\alpha = (11{,}5 \pm 1) \times 10^{-6}\ \text{K}^{-1}$, and therefore a value of $u(\alpha) = 0{,}58 \times 10^{-6}\ \text{K}^{-1}$ should be taken if no individual calibration value is available.

6.2.3 Uncertainty due to the input temperature of the material standards of size, $u(\varepsilon_t)$

This uncertainty component should be considered only for thermally-compensated CMMs, and only when the compensation relies on the temperature of the material standard of size, as measured by the tester by means of his own thermometers. When the temperature is measured by means of CMM-embedded thermometers, or when a CMM is not thermally compensated, this uncertainty component should be discarded, i.e. a value $u(\varepsilon_t) = 0$ should be used in Equation 4.

The recommended equation for this uncertainty component is

$$u(\varepsilon_t) = L \times \alpha \times u(t) \tag{7}$$

where

L is the size of the material standard being measured;

α is the CTE of the material standard of size;

$u(t)$ is the standard uncertainty of the temperature of the material standard of size.

To evaluate the input uncertainty $u(t)$, the following components are suggested for consideration.

— The calibration uncertainty of the thermometer(s) used is reported in the calibration certificate of the thermometer(s). The expanded uncertainty, U, reported in the certificate shall be transformed into the standard uncertainty, u, by dividing by the coverage factor, k, $u = U/k$. The value of k is also reported in the certificate, the most common value being $k = 2$.

— The uncertainty due to temperature variation during the test is best derived from experience with standards of similar thermal properties. In the absence of such experience, the approximate value $V_t / \sqrt{3}$ is recommended, where V_t is the span of the temperature difference between any two points on or in the material standard of size.

— When the recommendations in A.3.2.4 are followed, other uncertainty components are likely to be negligible.

The standard uncertainties obtained as above are summed in quadrature.

6.2.4 Uncertainty due to misalignment of the material standard of size, $u(\varepsilon_{\text{align}})$

It is recommended that care be taken to keep this component to a minimum. A.3.2.5 gives guidance on good metrological practice in this respect. When this guidance is followed, the component is likely to be negligible, i.e. a value $u(\varepsilon_{\text{align}}) = 0$ should be used in Equation 4.

However, this may not be true in all cases. A careful reading of A.3.2.5 is recommended to ascertain whether the actual circumstances determine a non-zero contributor, and, if so, to model and evaluate it.

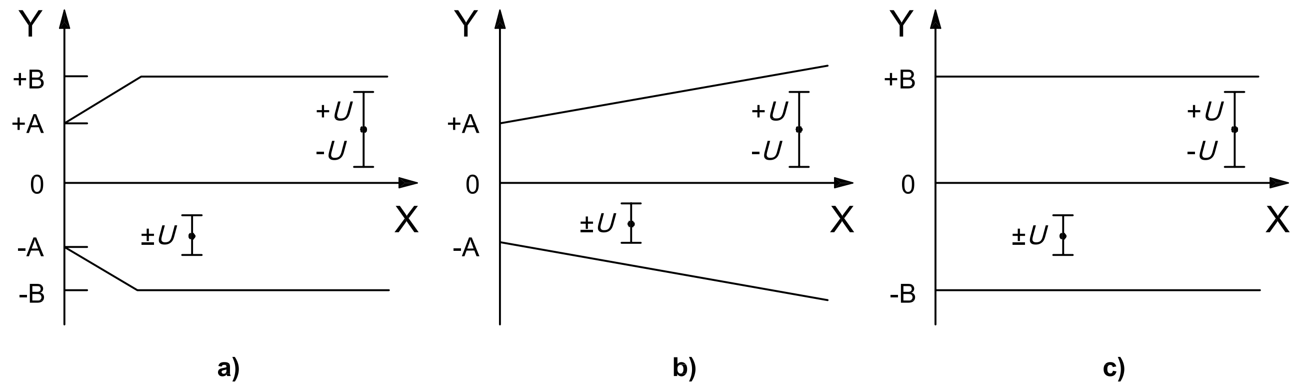
6.2.5 Uncertainty of fixturing the material standard of size, $u(\varepsilon_{\text{fixt}})$

It is recommended that all care be taken to keep this component to a minimum. A.3.2.6 gives guidance on good metrological practice in this respect. When this guidance is followed, the component may be negligible, i.e. a value $u(\varepsilon_{\text{fixt}}) = 0$ should be used in Equation 4.

However, this may not be true in all cases. A careful reading of A.3.2.6 is recommended to ascertain whether the actual circumstances determine a non-zero contributor, and, if so, to model and evaluate it.

6.3 Graphical representation of the test results

In accordance with ISO 10360-2:2001, 5.3.4, the values of E obtained should be plotted in a diagram (see Figures 1 and 2). Two alternative and equivalent representations are possible to deal with the test uncertainty, $U(E)$ (see ISO 14253-1:1998, Figures 6 to 11).



Key

X size, L, expressed in millimetres, of the material standard being measured

Y error of indication, E, expressed in micrometres

A positive constant, expressed in micrometres and supplied by the manufacturer

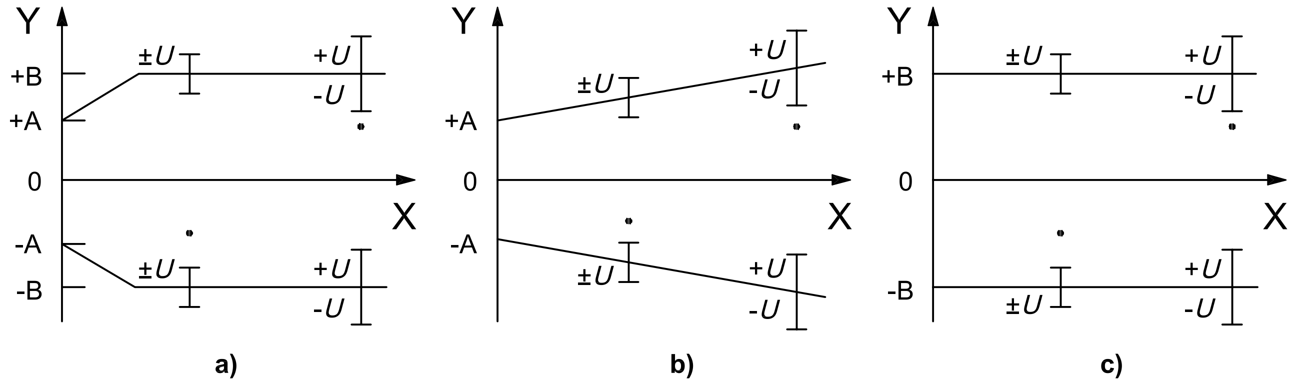
B maximum permissible error MPE_E, expressed in micrometres, as stated by the manufacturer

U expanded uncertainty

NOTE 1 Points with bars represent the values of E, and simple lines represent the MPE_E. The bar lengths represent the uncertainties $\pm U(E)$, and the central points represent the values obtained for the errors of indication.

NOTE 2 Only two values of E plotted for simplicity.

Figure 1 — Types of diagrams for the plotting of E, in accordance with ISO 10360-1:2000, 9.2



Key

X size, L, expressed in millimetres, of the material standard being measured

Y error of indication, E, expressed in micrometres

A positive constant, expressed in micrometres and supplied by the manufacturer

B maximum permissible error MPE_E, expressed in micrometres, as stated by the manufacturer

U expanded uncertainty

NOTE 1 Points represent the values of E, and simple lines represent the MPE_E. The bar lengths centred on the boundary lines represent the uncertainties $\pm U(E)$.

NOTE 2 Only two values of E plotted for simplicity.

Figure 2 — Alternative types of diagrams for the plotting of E, in accordance with ISO 10360-1:2000, 9.2

Annex A
(normative)

Background and more detailed information

A.1 Background

A.1.1 General

This annex gives background and details on the uncertainty evaluation described in the main body. It includes a general error model of the quantities tested in accordance with ISO 10360-2 (i.e. the probing error, P, and the error of indication, E) to help testers in evaluating the test uncertainty. As there are only a small number of main uncertainty contributors, which are typical in most common circumstances, the simplified equations for the test uncertainty given in the main body are derived. In addition, other possible uncertainty contributors are listed. A careful analysis of the actual circumstances is recommended, in order to ascertain whether a given listed contributor is, in fact, negligible.

A.1.2 Standard procedure

The standard procedure described in GUM and ISO/TS 14253-2 should be followed to evaluate all input uncertainties and to combine them into the combined uncertainty.

NOTE For convenience, it is worth noting that in the likely case that all contributors are statistically uncorrelated, the combined uncertainty is derived as the quadratic summation.

$$u_c(y) = \sqrt{c_1^2 u^2(x_1) + c_2^2 u^2(x_2) + \ldots + c_n^2 u^2(x_n)} \qquad \text{(A.1)}$$

where $u_c(y)$ is the combined (overall) standard uncertainty, the $u(x_i)$'s are the input standard uncertainties of contributors, and the c_i's are their sensitivity coefficients, obtained by derivation from the error model. Once the combined standard uncertainty $u_c(y)$ is evaluated, the expanded uncertainty $U(y)$ is obtained by multiplying by a coverage factor, k

$$U(y) = k \times u_c(y) \qquad \text{(A.2)}$$

The value $k = 2$ shall be used.

A.1.3 Different test results due to repeated testing

The number of measurements standardized by ISO 10360-2 is a compromise between thoroughness and the practical and economical implementation of the test. Two separate tests carried out on the same CMM, even if assumed to be time-invariant, may lead to different probing errors, P, and errors of indication, E, for the following reasons.

a) **Choice of test locations**. The purchaser (for the acceptance test) may decide on the locations for the test sphere and the material standards of size in the CMM volume (see ISO 10360-2:2001, 5.2.3.1 and 5.3.3.1). The test result is very sensitive to the choice of these locations, particularly for the test on size, e.g. a location along a volumetric diagonal usually provides a more severe test than one along a CMM axis. As a result, different choices of locations may lead to different errors of indication.

b) **Environmental conditions**. The test shall be performed in environmental conditions compatible with the specifications in the CMM operating manual, usually expressed as ranges. In practice, the actual test is performed in one particular condition only, as it is usually impossible, and certainly not economical, to repeat the test many times while varying temperatures, gradients, vibrations, etc. The strong sensitivity of CMM performance to 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 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, even if both tests are permissible.

c) **CMM repeatability**. Repeated measurements of the same measurand lead to slightly different results, due to such factors as probing noise, vibrations, backlash, etc. As each material standard of size 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 definition of the test, which specifies the number of different repeated measurements, and allows the test to be performed just once if the manufacturer's environmental specifications are met. The rationale for this is the compromise to make the test economically feasible, based on the educated experience that most CMM behaviour is determined by this test, and the awareness that more extensive coverage would only be achieved at an unacceptable cost of implementing the test.

Errors caused by the test reproducibility are therefore not the responsibility of the tester, who should not be held accountable for them, i.e. there is no corresponding ε for this in the error models in A.2.1 and A.3.2.

NOTE 1 The effect of the test reproducibility does not necessarily show up in the probing error and in the error of indication.

NOTE 2 The effects of test reproducibility do not necessarily change the test result, i.e. make the difference between acceptance and rejection. This issue is in any case of no consequence in this Technical Specification, whose main purpose is to evaluate the test uncertainty independent of its consequence on the test result.

A.1.4 Probing errors

The probing system is an integral part of the CMM. Any probing error is therefore not the responsibility of the tester, and no uncertainty component shall be added to the test uncertainty.

NOTE Probing errors show up in the value of the error of indication, E. It is therefore advisable for CMM manufacturers (for acceptance tests) and users (for reverification test) to set MPE_E values which incorporate these errors.

A.2 Test of probing error

A.2.1 Recommended model

The recommended model for the probing error, P, is

$$P = R_{\mathrm{max}} - R_{\mathrm{min}} = (R_{\mathrm{pt,max}} + \Delta R_{\mathrm{max}}) - (R_{\mathrm{pt,min}} + \Delta R_{\mathrm{min}}) = P_{\mathrm{pt}} + \varepsilon_{\mathrm{form}} \quad \text{(A.3)}$$

where

R_{max}, R_{min} are the maximum and minimum Gaussian radial distances measured by the CMM;

$R_{\mathrm{pt,max}}$, $R_{\mathrm{pt,min}}$ are the Gaussian radial distances of the same probed points as R_{max} and R_{min}, obtained while performing the test in an ideal way, i.e. with a perfect test sphere;

ΔR_{max}, ΔR_{min} are the radial form deviations of the test sphere at the same probed points as R_{max} and R_{min};

P_{pt} is the probing error obtained through an ideal test, i.e. when a perfect test sphere is used;

$\varepsilon_{\mathrm{form}} = \Delta R_{\mathrm{max}} - \Delta R_{\mathrm{min}}$ is the test sphere form error at the same probed points as R_{max} and R_{min}.

The second term in the above model equation stems directly from the definition of P (see ISO 10360-1:2000, 9.3 and ISO 10360-2:2001, 5.2.4).

The third and fourth terms highlight the form deviations of the test sphere. If the test were run with a perfect test sphere, the form error, $\varepsilon_{\text{form}}$, would be zero, and the value of the probing error obtained would be P_{pt}, which is indeed the value sought.

No other uncertainty contributors are expected for the probing error, P, in normal circumstances.

Due to the simple structure of the error model, the standard uncertainty of the probing error is simply the standard uncertainty of the contributor $\varepsilon_{\text{form}}$

$$u(P) = u(\varepsilon_{\text{form}}) \tag{A.4}$$

The recommended expression for the uncertainty caused by the form error is

$$u(\varepsilon_{\text{form}}) = \sqrt{\left(\frac{F}{2}\right)^2 + u^2(F)} \tag{A.5}$$

where

F is the form error reported in the calibration certificate;

$u(F)$ is the standard uncertainty of the form error stated in the calibration certificate.

NOTE 1 The form error is always positive and hence cannot have a mean of zero. A rigorous application of the GUM would require a correction of the systematic error (see GUM:2003, F.2.4.5), which is not indicated in ISO 10360-2 and is usually impractical. The above equation assumes no correction, but overestimates the first term slightly. However, the value of F is usually small in practice, and the overestimation is unlikely to affect the test significantly.

NOTE 2 The highest (peak) and lowest (valley) point pairs, which dictate the probing error, P, and the form error, F, do not necessarily coincide because of probing effects, as well as the limited number of sampling points. As a consequence, the effect of the form error on the probing error, P, can be smaller than the calibration value $F/2$.

A.2.2 List of other possible contributors

The recommended model in A.2.1 is likely to be adequate in most circumstances. However, the tester is urged to investigate whether more uncertainty contributors are relevant in his specific application.

The following contributors may be relevant in some applications.

— **Fixturing of the test sphere**. If the test sphere is fixtured loosely or vibrations are present, the test sphere may shift during the measurements, e.g. due to probing forces, vibrations and inertial forces. Firm fixturing of the test sphere usually makes this contributor negligible.

— **Bending of the test sphere stem**. If the test and reference sphere stems exhibit different rigidities, the bending due to probing forces may cause errors. Commercially available test spheres usually make this contributor negligible.

A.3 Test of size

A.3.1 General model

A.3.1.1 Basics

The test of size measurement is based on the evaluation of the error of indication, E. The recommended general model for E is

$$E = x_{\text{read}} - x_{\text{cal}} = (x_{\text{pt}} + \varepsilon_1 + \varepsilon_2 + \ldots \varepsilon_n) - (X + \varepsilon_{\text{cal}}) = E_{\text{pt}} - \varepsilon_{\text{cal}} + \varepsilon_1 + \varepsilon_2 + \ldots \varepsilon_n \quad \text{(A.6)}$$

where

x_{read} is the CMM reading while measuring the material standard of size;

x_{cal} is the calibration value of the material standard of size;

x_{pt} is the CMM reading while performing the test perfectly, i.e. when the tester would not introduce any error at all;

ε_i is one of the errors in the CMM reading, introduced by the tester;

X is the (unknown) true value of the material standard of size;

ε_{cal} is the calibration error of the material standard of size;

$E_{\text{pt}} = (x_{\text{pt}} - X)$ is the error of indication obtained through a perfect test, i.e. when the tester would use a perfectly-calibrated material standard of size and not introduce any error at all.

The second term in the above model equation is simply the definition of E (see VIM:1993, 5.20, ISO 10360-1:2000, 9.1 and ISO 10360-2:2001, 5.3.4).

The third term highlights the errors in the tester's responsibility. If the test were run in perfect conditions, all ε_i errors would be zero, and the CMM reading would be x_{pt}.

Also, if the material standard of size were perfectly calibrated, i.e. zero ε_{cal}, the value obtained for the error of indication E would be E_{pt}, which is indeed the value sought.

Each term ε may either require further modelling (transparent box evaluation, see ISO/TS 14253-2:1999, 8.7) or be evaluated as a whole (black box evaluation, see ISO/TS 14253-2:1999, 8.6), the former being recommended whenever possible.

Due to the simple additive structure of the error model, all sensitivity coefficients are equal to unity, and the uncertainties, $u(\varepsilon)$, are summed in quadrature.

NOTE 1 The ε_i terms have unknown values and signs, and cannot be compensated for: they are present in the error model as contributors to the test uncertainty. In probability terminology (see GUM), they are zero-mean random variables with standard deviations taken as standard uncertainties.

NOTE 2 The minus sign of the calibration error, ε_{cal}, stems from the calibration value, x_{cal}, being a subtrahend in the definition of the error of indication, E. The sign is of no importance to the uncertainty, $u(\varepsilon_{\text{cal}})$, which is always positive.

A.3.1.2 ε_i errors due to thermal or other software compensations

A tester may introduce, ε_i, errors not only through the material standard of size (e.g. through misalignment or clamping), but also through imperfect information provided to compensate CMM errors. This occurs when a software-compensated CMM needs input information (e.g. the CTE): any error in this information affects the value of E. Because the tester inputs the information, he takes the responsibility, and the error model records this as an error ε_i.

Software compensators compute corrections on the basis of pre-defined equations. When a compensator needs information input by the tester, the underlying equation should be used as an analytical model for the corresponding ε_i. If this is not shown, the CMM manufacturer should be questioned about the model. Alternatively, the equation may be guessed in some simple and obvious cases, i.e. when a widely-recognized model is available for the correction. This is the case for the thermal contributors considered in the recommended simplified model in A.3.2.

Any error compensation without the need for information input by the tester (e.g. for geometrical errors, usually done at lower levels of the CMM software or by the CNC) should be regarded as an integral part of the CMM and is not the tester's responsibility. Therefore, it should not be included in the error model as a term ε_i.

A.3.2 Recommended simplified model

A.3.2.1 Basics

The following simplified model is recommended for usual circumstances:

$$E = E_{\text{pt}} - \varepsilon_{\text{cal}} + \varepsilon_{\alpha} + \varepsilon_t + \varepsilon_{\text{align}} + \varepsilon_{\text{fixt}} \quad \text{(A.7)}$$

where

ε_{cal} is the calibration error of the material standard of size;

ε_{α} is the error due to the input value of the CTE of the material standard of size;

ε_t is the error due to the input value of the temperature of the material standard of size;

$\varepsilon_{\text{align}}$ is the error due to misalignment of the material standard of size;

$\varepsilon_{\text{fixt}}$ is the error due to fixturing the material standard of size.

A.3.2.2 Calibration errors of the material standards of size, ε_{cal}

The material standard of size shall be calibrated. The calibration certificate states the calibration uncertainty, U_{cal}, and the coverage factor, k, used (typically $k = 2$). The uncertainty contributor, $u(\varepsilon_{\text{cal}})$, is obtained by dividing the calibration uncertainty by the coverage factor

$$u\left(\varepsilon_{\text{cal}}\right) = \frac{U_{\text{cal}}}{k} \quad \text{(A.8)}$$

If two or more gauge blocks are wrung together to achieve a certain size, the individual uncertainties shall be combined, taking into account possible correlations. In the typical situation when the gauge blocks are taken from the same set, calibrated by the same laboratory at the same time, the correlation may be large, and a linear, rather than quadratic, summation is sometimes recommended. Otherwise, the correlation should be investigated and properly treated. An additional uncertainty contributor may be introduced to account for the wringing. This contributor especially should be considered when coupling clamps are used that may be over-tightened.

A.3.2.3 Errors in the CTE of the material standards of size, ε_α

When the built-in thermal compensation of the CMM asks the tester for the CTE of the material standard of size, any error in the input value results in an error in the CMM indication. For most CMMs, this error is

$$\varepsilon_\alpha = -L \times (t - 20\ °\text{C}) \times \Delta\alpha \quad \text{(A.9)}$$

where

- L is the size of the material standard being measured;
- t is the temperature of the material standard of size;
- 20 °C is the reference temperature (see ISO 1);
- $\Delta\alpha$ is the (unknown) error of the CTE of the material standard of size.

The standard uncertainty, $u(\varepsilon_\alpha)$, is calculated as

$$u(\varepsilon_\alpha) = L \times (|t - 20\ °\text{C}|) \times u(\alpha) \quad \text{(A.10)}$$

Some compensation software may provide a predefined list of materials (e.g. steel, aluminium) to choose from. If an option is available (e.g. "others") to input an actual CTE numerical value, the tester should choose it even if the material of his standard of size is mentioned in the list. Whether or not an actual CTE numerical value is input, the contributor, $u(\varepsilon_\alpha)$, should be considered in Equation 4.

A.3.2.4 Errors in the input temperature of the material standards of size, ε_t

A.3.2.4.1 According to the ISO 10360-2 procedure, the thermal condition in which the test is performed shall meet the specifications stated by the CMM manufacturer. This is a prerequisite for a valid test. Within the specified limits, some CMMs may compensate for thermal expansion: to do so, they need the temperature value of the material standard of size.

Temperature measurement errors may occur due to the following causes:

a) calibration errors of the thermometer(s);

b) temperature variations during the test;

NOTE The error is due to the delay of the temperature of the material standard of size relative to that of the thermometer(s), and vice versa. This delay is due to different time constants of the material standard of size and of the thermometer(s), to the propagation time from the skin surface in contact with the environment to the core, and to poor temperature sampling, i.e. few temperature measurements during long measurement tasks.

c) radiation from the environment to the thermometer(s) and thermal contact with the material standard of size;

d) a thermal gradient along the material standard of size, which affects the measured value of the average temperature.

A.3.2.4.2 The following are recommended to reduce the causes listed in A.3.2.4.1.

a) The calibration uncertainty of the thermometer(s) should match the actual measurement requirement: when this uncertainty contributor is dominant in the test uncertainty budget, consider a better calibration.

b) In long measuring tasks, program frequent temperature measurements when this option is available. When the tester has no control over the temperature sampling rate, split long measuring tasks into shorter ones, in order to force sufficiently frequent temperature measurements.

c) Radiation is blocked by reflecting shields: the thermal contact is improved by matching surface geometries (e.g. flat on flat) and by use of contact grease. The tester is advised to shield the thermometer(s) (e.g. by means of an insulating material wrapped in aluminium foil), and to contact the thermometer(s) to the material standard of size with a thermal contact grease formulated to improve thermal contact (e.g. heat sink grease).

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 central point of the material standard of size, at a distance of approximately $0{,}211 \times L$ from the ends (Airy points). The mean value should be used as the effective temperature. If only one thermometer is available, it is recommended to put it at the central point of the material standard of size, and to wait for an additional settling time.

NOTE The Airy points are also the prescribed resting points for long gauge blocks (see ISO 3650:1998, 5.4), and are often marked on their side faces.

A.3.2.4.3 Depending on the CMM equipment, either the CMM itself or the tester may measure the temperature, by means of either embedded thermometers or tester's thermometers. In the former case, the tester is not responsible for the thermal measurement, hence the temperature measurement should not be considered as an uncertainty contributor. A non-zero error ε_t should be included in the error model only for temperature-compensated CMMs when the temperature of the material standard of size is measured by the tester. In this case, any error in the temperature results in an error

$$\varepsilon_t = -L \times \alpha \times \Delta t \tag{A.11}$$

where

L is the size of the material standard being measured;

α is the CTE of the material standard of size;

Δt is the (unknown) error of the temperature of the material standard of size.

NOTE 1 When a CMM is temperature-compensated and provided with embedded thermometers, they are regarded as a part of the CMM. The measurement error, ε_t, is part of E_{pt} in the error model in this case, and does not give rise to any test uncertainty.

NOTE 2 The recommendations in bullets A.3.2.4.2 a) to d) apply even when the temperature is not included in the error model as a contributor.

The standard uncertainty, $u(\varepsilon_t)$, is calculated as

$$u(\varepsilon_t) = L \times \alpha \times u(\Delta t) \tag{A.12}$$

NOTE 3 As the temperature value is of vital importance for the thermal compensation, and hence for the test results, the use of uncalibrated thermometers is not recommended.

A.3.2.5 Misalignment of the material standard of size, $\varepsilon_{\text{align}}$

A.3.2.5.1 To measure the size of each material standard, the distance between two points at its ends is taken. However, supplementary measurements are needed for alignment (see ISO 10360-2:2001, 5.3.3.3). These two end points can be regarded as the intersection of the measuring faces with a straight line, which is often the first axis of a workpiece coordinate system taken on the material standard of size. Any imperfection or accident that occurs when this workpiece coordinate system is set results in misalignment.

Misalignment errors may be caused by the following:

a) non-identical definitions of the axis of the material standard of size at the calibration and at the testing stages (uncertainty method in ISO/TS 17450-2:2002, 3.5.4), e.g. a gauge block is calibrated mechanically between the centres of the measuring faces, but is aligned for testing on its side faces;

b) imperfect setting of the axis of the material standard of size due to probing errors and form deviation of the material standard of size, e.g. 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 targeting the two end points (i.e. the actual contact points differ from the target contact points), e.g. either the CNC or the tester (for manual CMMs) drives the stylus tip imperfectly.

A.3.2.5.2 The following are recommended to reduce the effect of the causes listed in A.3.2.5.1.

a) A good understanding of the definition of the calibration measurand (specification operator) is crucial in creating a proper alignment procedure. This definition should be given or referenced in the calibration certificate: a default definition for gauge blocks is given in ISO 3650. The direct implementation of such a definition (perfect verification operator) is recommended whenever possible, and particularly when the material standard of size has significant form errors, e.g. perpendicularity errors between the side and measuring faces. It is recommended to align the axes of each material standard of size separately, even when they 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 material standard of size 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). For example, a material standard of size, aligned on its side faces, is best sampled symmetrically about the centre in order to minimize the misalignment effect of bending (form error), and in points as far from each other as possible (e.g. at the extremes), in order to optimize the angular definition of the associated plane (best conditioning).

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 material standard of size before calculating the distance between them. When the axis of the material standard of size is taken as the first axis of a workpiece coordinate system, this is done most easily by taking the difference of the two point coordinates along that axis.

A.3.2.5.3 Misalignment results in two different errors, arising from

— confusing a hypotenuse (the measured quantity) with a side (the measurand), often referred to as cosine error;

— lack of parallelism of the measuring faces, giving different values for measurements along parallel lines.

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

$$\varepsilon_{\text{align}} = e_{\text{cos}} + e_{\text{parall}} \qquad \text{(A.13)}$$

with

$$e_{\cos} = \frac{\theta^2}{2} L, \quad \theta = \frac{\left(p_1 + p_{\text{geo1}}\right) - \left(p_2 + p_{\text{geo2}}\right)}{L_{\text{align}}} \tag{A.14}$$

where

$e_{\cos}$	is the cosine error;
e_{parall}	is the parallelism error of the measuring faces of the material standard of size;
θ	is the misalignment angle;
L	is the size of the material standard being measured;
p_1, p_2	are the unidirectional probing errors, in the direction of probing the alignment points;
$p_{\text{geo1}}, p_{\text{geo2}}$	are the form errors at the alignment points, i.e. their lateral deviations from the axis of the material standard of size defined for 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 modelled here in a plane (2D) for sake of simplicity. In the 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 millimetres).

NOTE 2 When the definition of the axis of the material standard of size is the same as that used for calibration (perfect verification operator), the errors p_{geo1} and p_{geo2} are zero.

NOTE 3 In the case of gauge blocks, the axis of the material standard of size is defined in ISO 3650 as normal to one of the measuring faces. When the side faces are used instead to align the material standard of size in the test, p_{geo1} and p_{geo2} are the perpendicularity errors (see ISO 3650:1998, 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 ($L_{\text{align}} \approx L$ for gauge blocks), and $u(p_{\text{geo}})$ can be derived from the specification of the material standard of size.

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 Equation A.14 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.

A.3.2.5.4 The standard uncertainty, $u(\varepsilon_{\text{align}})$, is calculated as

$$u\left(\varepsilon_{\text{align}}\right) = \sqrt{u^2\left(e_{\cos}\right) + u^2\left(e_{\text{parall}}\right)} \tag{A.15}$$

with

$$u\left(e_{\cos}\right) = 2\sqrt{2}\,\frac{u^2(p) + u^2\left(p_{\text{geo}}\right)}{L_{\text{align}}^2} L \tag{A.16}$$

where

$u(p) = u(p_1) = u(p_2)$ are the standard uncertainties of the unidirectional probing error

$u(p_{geo}) = u(p_{geo1}) = u(p_{geo2})$ are the standard uncertainties 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;

$u(e_{parall})$ is the parallelism standard uncertainty.

NOTE 1 It is assumed that the uncertainties of p_1, p_2 and of p_{geo1}, p_{geo2}, respectively, are equal at the alignment points.

NOTE 2 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 (see GUM:2003, F.2.4.4), which is usually impractical. The above equation requires no correction but overestimates the cosine uncertainty by 41 %.

NOTE 3 The uncertainty of L_{align} is negligible, being of second order.

NOTE 4 When the distance from the extreme alignment points is equal to the measured size, $L_{align} \approx L$, and the cosine error is inversely proportional to the size.

The cosine contributor, $u(e_{cos})$, is tabulated in Table A.1 for illustration.

Table A.1 — Examples of values of the uncertainty, $\frac{u(e_{cos})}{L} \times 10^6$, due to the cosine error

$u(p_{geo})$ µm	$u(p)$ µm	L_{align} mm			
		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
NOTE A value of e.g. 1,96 in the table corresponds to $u(e_{cos}) = 1{,}96 \times 10^{-6} \times L$.					

To evaluate the input uncertainties, the following are suggested.

— $u(p)$ is the unidirectional repeatability of the CMM. It can be evaluated either as the standard deviation of repeated unidirectional measurement of a plane surface, $u(p) = \sigma$ (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, as P is derived from multi-directional measurements. If the standard uncertainty obtained is considered too large, repeating the probing cycle of the datums used for alignment reduces this uncertainty by means of averaging, i.e. $u(p) = u_{single}(p)/\sqrt{n}$ where $u_{single}(p)$ is the standard uncertainty obtained for a single probing cycle, and n is the number of probing cycles.

— $u(p_{geo})$ is non-zero only when the definition of the axis of the material standard of size is not the same as that used for calibration. In this case, it can be derived from the tolerance T, set on the surfaces of the material standard of size used for alignment, with the axis used for calibration as a datum, $u(p_{geo}) = T/\sqrt{12}$. For gauge blocks, T is the perpendicularity tolerance, and its value is set in ISO 3650:1998, Table 4.

— $u(e_{parall})$ can be derived from the parallelism tolerance, $T_{//}$, set on the measuring faces of the material standard of size, $u(e_{parall}) = T_{//}/\sqrt{12}$. For gauge blocks, $T_{//}$ is the tolerance of the variation in length, v, i.e. $T_{//} = t_v$, and its value is set in ISO 3650:1998, Table 5. This value of $u(e_{parall})$ is likely to be overestimated, as the area where the axis of the material standard of size may strike a measuring face is usually significantly smaller than the measuring face.

A.3.2.6 Fixturing of the material standard of size, $\varepsilon_{\text{fixt}}$

A.3.2.6.1 Fixturing may cause deformation of the material standard of size, due to clamping, inertial and probing forces. Even if expansion caused by lateral shrinkage occurs, 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 (i.e. e_{parall} in A.3.2.5 is larger);

b) the datums used to define the axis of the material standard of size (e.g. two side faces) are deformed, so the axis orientation and location have larger uncertainties (i.e. p_{geo1} and p_{geo2} in A.3.2.5 are larger);

c) when the measurement points on the measuring faces are off the neutral axis of the material standard of size, the bending brings them either closer to or further from each other, depending on the vector to the neutral axis.

NOTE 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. In addition, many step gauges are designed with their measuring faces on the neutral axis, or with sufficient rigidity.

Rocking may occur from probing forces and inertial forces (moving table CMMs only), both in hysteresis and elastically, i.e. respectively with or without residual effects after the force causing the rocking ends.

A.3.2.6.2 The following steps are recommended to reduce the effects listed in A.3.2.6.1.

— The magnitude of clamping forces should be kept to a minimum to avoid unnecessary deformation.

— In view of its particular design, the fixturing points should be chosen carefully on the material standard of size, in order to minimize deformation and to follow the manufacturer's directions whenever possible. The fixturing points are best chosen if they are symmetric about the centre of the material standard of size, 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 material standard of size is very important for minimizing clamping deformation. When true kinematic mountings are not practical, the seats should be minimally over-determined, i.e. minimally over-constrained.

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

— The support should be sufficiently rigid in the measuring direction. This includes the entire coupling chain from the material standard of size to the CMM base or table, i.e. the seats, support body, and clamping to the CMM base.

A.3.2.6.3 An explicit model of the fixturing error, $\varepsilon_{\text{fixt}}$, is difficult to obtain, and a black box approach may be followed. The following are suggested.

a) By experiment, in two steps.

   1) A preliminary size measurement is repeated twice (L_{b1} and L_{b2}), the second time (L_{b2}) after doubling the clamping forces, with $\Delta L_b = (L_{b2} - L_{b1})$ being the difference between the two size measurements.

   2) A dial gauge, or similar measuring device, is fixtured in contact with a measuring face and zeroed, with ΔL_{p1} being the dial gauge reading when a force imitating the probing force is applied to the other measuring face. The force generator and the dial gauge are then swapped, with ΔL_{p2} being the reading.

   A rough estimate of the fixturing uncertainty is $u(\varepsilon_{\text{fixt}}) = |\Delta L_b - (|\Delta L_{p1}| + |\Delta L_{p2}|)|$.

b) *A priori*, when the above evaluation is not possible or impractical (e.g. because there are no means of changing the clamping forces without introducing thermal perturbations by handling), an educated guess may be the only alternative.

NOTE It is recommended that care be taken in the experimental evaluation described in a), when imitating the probing force, because some probing systems indicate the measurement result before the full probing force is applied (e.g. some touch-trigger probing systems), whereas others extrapolate the measurement result to nearly zero force after the full probing force is applied (e.g. some proportional probing systems). While elastic effects are sensitive only to the force at the actual instant of measurement (e.g. at latching for most touch-trigger probing systems, or at the extrapolated force for most proportional probing systems), the hysteresis is sensitive to the maximum force applied while probing. Ideally, the force generator imitates the complete force pattern and maintains the force at the actual instant of measurement, in order to allow the dial gauge enough time to give a reading.

A.3.3 List of other contributors which are possible

The recommended simplified model in A.3.2 is likely to be adequate in most circumstances. However, the tester is urged to investigate whether other uncertainty contributors are relevant in his specific application.

The following contributors may be relevant in some applications.

— **Magnetisation of the material standard of size**. When the material standard of size is not fully demagnetized, the stylus may be attracted and give false measurements.

— **Dead weight**. When the material standard of size is either resting or hanging in a vertical position, its own weight will either compress or expand it, respectively.

— **Cleanliness of the material standard of size**. The tester is urged to clean the material standards of size thoroughly before starting the test. Any dust and grease residuals may introduce probing errors.

— **Potential damage**. The tester is urged to handle the material standard of size with great care. Mechanical and thermal shocks that occur, particularly during transportation, may alter the calibrated sizes. When damage is suspected, it is recommended either to re-calibrate the material standard of size, or to add an additional uncertainty contributor.

— **CMM operator**. It is strongly recommended that the person(s) performing the test be sufficiently trained and experienced, in order to avoid improper applications of the test.

Annex B
(normative)

Using an alternative material standard of size

B.1 General

A question may arise as to whether the tester counterpart is allowed to provide a material standard of size in an acceptance test, and how to deal with the test uncertainty in that case. ISO 10360-2 neither allows nor prohibits this, and, in principle, any correctly-calibrated material standard of size is equivalent to any other within its calibration uncertainty. The tester counterpart may therefore wish to have his own material standard of size used in the test, as a further guarantee of the test transparency.

NOTE This situation cannot occur in a reverification test, as the tester and the tester counterpart coincide in this case (see also 3.3 NOTE 2).

Even if nominally physically equivalent, the two material standards of size provided by the parties may differ in their calibration uncertainties. When the tester's uncertainty is smaller than that of the tester counterpart, the resulting expansion of the uncertainty zone may prevent a tester from proving conformance or non-conformance, through no fault of his own.

B.2 Procedure

When the tester counterpart wishes to use his material standard of size, two complete budgets of the test uncertainty should be established at the time of use, one for each material standard of size, which by mutual agreement assume a temperature deemed to be representative of the actual situation. The tester is then required to use the material standard of size of the tester counterpart, or to allow him to execute the test only if the associated test uncertainty is not greater than that of the tester. In any case, the test uncertainty of the actual material standard of size should be used for proving conformance or non-conformance, which may result in an increase of the conformance zone.

In the special case of a CMM with no capability for thermal compensation of the workpiece, the material standard of size of the tester counterpart shall be steel by default, if that of the tester is also steel. In other (non-steel) cases, there shall be mutual agreement between the two parties regarding the CTE of the material standard of size of the tester counterpart.

Since the tester is prepared to perform the test with his own material standard of size, the use of that of the tester counterpart may require additional time and labour, the costs of which should be agreed upon during the contract negotiations.

NOTE It is recommended that special attention be paid when the same material standard of size is used both for the test and for mapping and compensating the CMM errors. This can occur when the test immediately follows a CMM error mapping done by the tester himself. Cancellation of errors cay occur in this case, as the CMM is tested in almost exactly the same conditions as those in which it was error-compensated, which results in a loss of test sensitivity, i.e. the values of the error of indication, E, are too small. When the use of different material standards of size for mapping and testing is impractical or too expensive, it is recommended that the tester counterpart choose the seven test locations only after the error mapping.

Annex C
(informative)

Examples of uncertainty budgeting

C.1 General

The numerical examples given in this annex focus exclusively on the test uncertainty, which means that no measurement values are dealt with. The graphical representations of the test results given in the examples are drawn in accordance with Figure 2 instead of Figure 1 for this reason only, and are not a recommendation for either form.

In addition, no decision rules are applied in the absence of measurement values. In practical cases, once the test uncertainty has been evaluated, the ISO 14253-1 decision rule should be applied.

Gauge blocks and step gauges are used in the examples for illustration only. Their use does not constitute a recommendation as to which material standard of size is best in general, or in particular circumstances.

C.2 Example 1

C.2.1 General

An industrial CMM in a workshop with minimal separation from the warehouse is tested for acceptance, by means of a test sphere and a step gauge, both made of steel. The specifications of the CMM and of the equipment used are indicated in Table C.1; they are taken from the CMM and step gauge data sheets, and from the calibration certificates of the test sphere and of the step gauge.

Table C.1 — Specification of the CMM and of the equipment used

CMM	Measuring volume	$(1200 \times 700 \times 600)$ mm^3
	MPE_P	2,5 µm
	MPE_E	$\pm (4 + L / 100)$ µm
	No thermal compensation	
Test sphere	Calibrated form error, F	$(0,23 \pm 0,15)$ µm
Step gauge	Calibration uncertainty of the size	0,5 µm + $1,0 \times 10^{-6} L$
	CTE	unknown
	Perpendicularity tolerance of the measuring faces with the gauge axis as datum.	2 µm

C.2.2 Test of probing error

The value of $u(F)$ is derived from the certificate as

$$u(F) = \frac{U(F)}{k} = \frac{0{,}15\ \mu\text{m}}{2} = 0{,}075\ \mu\text{m} \qquad \text{(C.1)}$$

The uncertainty $u(P)$ is evaluated by the equation

$$u\left(\varepsilon_{\text{form}}\right)=\sqrt{\left(\frac{F}{2}\right)^2+u^2\left(F\right)} \tag{C.2}$$

which in this case amounts to

$$u\left(P\right)=\sqrt{\left(\frac{0{,}23\ \mu\text{m}}{2}\right)^2+\left(0{,}075\ \mu\text{m}\right)^2}=0{,}14\ \mu\text{m} \tag{C.3}$$

With a coverage factor $k = 2$, the test uncertainty is

$$U(P) = k \times u(P) = 2 \times 0{,}14\ \mu\text{m} = 0{,}28\ \mu\text{m} \tag{C.4}$$

This amounts to 11 % of the MPE_P, which may be considered adequate for the test.

C.2.3 Test of size

C.2.3.1 General

The shortest size is taken to be 10 mm (see ISO 10360-2, 5.3.2.1). As the spatial diagonal of the working volume is 1 513 mm, the longest size shall not be shorter than 999 mm. Consequently, a 1 010 mm length is taken, also considering the requirement for faces to be in opposite directions. As this length is larger than the CMM travel in y and z, additional intermediate lengths are taken to fit the different axes. The resulting combination of lengths and of the associated calibration uncertainties is given in Table C.2.

Table C.2 — Selection of lengths used and their calibration uncertainties

L, mm	10	110	250	510	590	690	1 010
$U(\varepsilon_{\text{cal}})$, µm	0,51	0,61	0,75	1,01	1,09	1,19	1,51

The uncertainty $u(E)$ is evaluated by the equation

$$u\left(E\right)=\sqrt{u^2\left(\varepsilon_{\text{cal}}\right)+u^2\left(\varepsilon_{\alpha}\right)+u^2\left(\varepsilon_t\right)+u^2\left(\varepsilon_{\text{align}}\right)+u^2\left(\varepsilon_{\text{fixt}}\right)} \tag{C.5}$$

NOTE The test uncertainties of the measurements of each length can vary with location and orientation, e.g. due to different thermal or fixturing uncertainty components. For simplicity, this is assumed not to be the case in this particular example.

C.2.3.2 Uncertainty due to the calibration of the material standards of size, $u(\varepsilon_{\text{cal}})$

This component is taken from the calibration certificate, dividing the reported value by the coverage factor, $k = 2$. The resulting values are given in Table C.3.

Table C.3 — Values of $u(\varepsilon_{\text{cal}})$ for the sizes used

L, mm	10	110	250	510	590	690	1 010
$U(\varepsilon_{\text{cal}})$, µm	0,26	0,31	0,38	0,51	0,55	0,60	0,76

C.2.3.3 Uncertainty due to the CTE of the material standards of size, $u(\varepsilon_\alpha)$

As the CMM is not thermally compensated, this component should not be included, $u(\varepsilon_\alpha) = 0$.

C.2.3.4 Uncertainty due to the input temperature of the material standards of size, $u(\varepsilon_t)$

As the CMM is not thermally compensated, this component should not be included, $u(\varepsilon_t) = 0$.

C.2.3.5 Uncertainty due to misalignment of the material standard of size, $u(\varepsilon_{\text{align}})$

The alignment procedure is chosen to be consistent with the definition of the calibrated sizes. A workpiece reference frame is set with two long side faces as the first two datums, and the resulting first axis translated onto the nominal central line of the step gauge.

NOTE 1 In practice, the CMM software might need an additional orientation about, and location along, the first axis, in order to set a fully defined workpiece reference frame, which is usually based on lateral faces. This is not considered here, as it is irrelevant to the test uncertainty.

The uncertainty $u(\varepsilon_{\text{align}})$ is evaluated by the equation

$$u\left(\varepsilon_{\text{align}}\right) = \sqrt{u^2\left(e_{\cos}\right) + u^2\left(e_{\text{parall}}\right)} \tag{C.6}$$

The input values needed to evaluate $u(e_{\cos})$ are estimated as follows:

— a value of $L_{\text{align}} = 1\,000$ mm is taken, as this is the distance between the extreme points probed on the side faces used for alignment;

— as the actual value in the test on the probing error is $P = 1{,}6$ µm, a value of $u(p) = P/\sqrt{12} = 0{,}46$ µm is taken;

— a value of $u(p_{\text{geo}}) = 0$ is taken, as the alignment is done following the definition of the calibrated size of the step gauge axis.

The resulting value of $u(e_{\cos})$ is

$$u\left(e_{\cos}\right) = 2\sqrt{2} \times \frac{u^2(p) + u^2\left(p_{\text{geo}}\right)}{L_{\text{align}}^2} L = 2\sqrt{2} \times \frac{(0{,}46\ \mu\text{m})^2}{(1000\ \text{mm})^2} L \approx 0 \tag{C.7}$$

where the length of the side faces used for alignment makes the cosine error negligible.

The uncertainty $u(e_{\text{parall}})$ is derived from the perpendicularity tolerance of the measuring faces, with the axis of the step gauge as a datum. As two faces are involved in each point-to-point measurement, the component should be considered twice, resulting in $u(e_{\text{parall}}) = (2\ \mu\text{m})/\sqrt{6} = 0{,}82$ µm.

NOTE 2 These values of $u(p)$ and $u(e_{\text{parall}})$ are overestimated, as P is derived from multi-directional measurements, and the perpendicularity tolerance accounts for the full area of the measuring face while the portion involved in the measurement is smaller. For simplicity, this is included at this stage, but can be reconsidered after the test uncertainty $U(E)$ has been evaluated, if it is considered too large (iterative approach of the PUMA method, see ISO/TS 14253-2).

C.2.3.6 Uncertainty of fixturing the material standard of size, $u(\varepsilon_{\text{fixt}})$

The step gauge is supported by the articulated mounting provided. It is very stiff, and the fixturing is not expected to cause significant effects. However, some thermal effects may occur due to the large variation in the environmental temperature, and to the different respective materials of the step gauge and its support.

An educated guess of this effect is $\leqslant 1$ µm, resulting in an uncertainty value of $u(\varepsilon_{\text{fixt}}) = (1\ \mu\text{m})/\sqrt{3} = 0{,}58$ µm (type B black box evaluation).

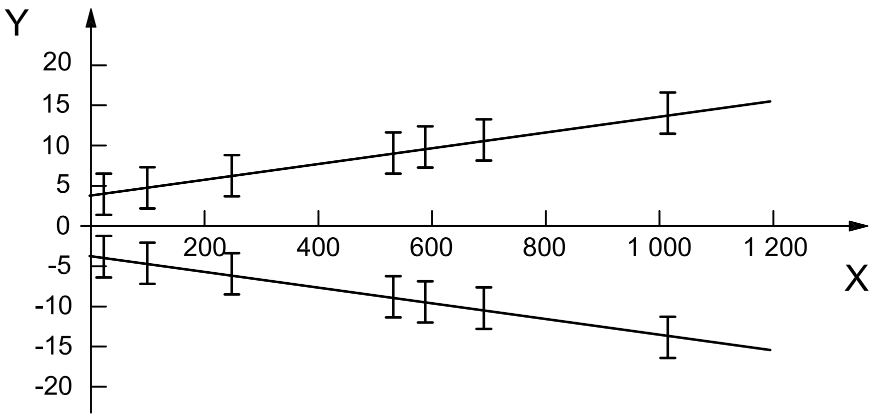
C.2.3.7 Budget and graphical presentation of the test uncertainty $u(E)$

Combining the above contributors results in the test uncertainty budget in Table C.4.

Table C.4 — Budget of the test uncertainty $u(E)$ (in micrometres)

	L mm						
	10	110	250	510	590	690	1 010
$u(\varepsilon_{cal})$	0,26	0,31	0,38	0,51	0,55	0,60	0,76
$u(\varepsilon_{\alpha})$	—	—	—	—	—	—	—
$u(\varepsilon_{t})$	—	—	—	—	—	—	—
$u(\varepsilon_{align})$	0,82	0,82	0,82	0,82	0,82	0,82	0,82
$u(\varepsilon_{fixt})$	0,58	0,58	0,58	0,58	0,58	0,58	0,58
$u(E)$	1,03	1,05	1,07	1,12	1,14	1,16	1,25
$U(E)$	2,06	2,09	2,14	2,24	2,28	2,33	2,51
	NOTE $U(E) = k \times u(E)$, a coverage factor $k = 2$ is used.						

The graphical representation of the MPE_E and of the test uncertainties is shown in Figure C.1.



Key

X size L, expressed in millimetres, of the material standard being measured

Y error of indication E, expressed in micrometres

Figure C.1 — Graphical representation of the MPE_E and of the test uncertainties

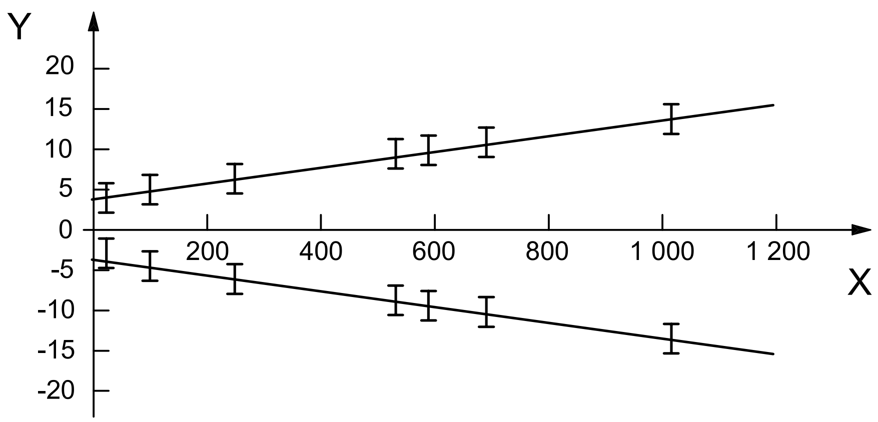
The test uncertainties range from 18 % to 50 % of the MPE_E and may be considered adequate for the test. However, these values are not optimal, particularly for short sizes. To improve this, the largest contributor should be addressed in an attempt to reduce the uncertainties (PUMA method, see ISO/TS 14253-2). The overestimation in the misalignment, introduced by counting the full measuring face as the probing area for evaluating the component $u(e_{parall})$, could be reconsidered. For instance, if the measuring face is 10 mm in diameter, and the probing area is estimated to be 1 mm in diameter, the resulting uncertainty is

$$u\left(e_{align}\right) = u\left(e_{parall}\right) = 0{,}82\ \mu\text{m}\frac{1\ \text{mm}}{10\ \text{mm}} = 0{,}08\ \mu\text{m} \quad \text{(C.8)}$$

The final test uncertainty budget and the graphical representation are indicated in Table C.5 and Figure C.2.

Table C.5 — Final budget of the test uncertainty $u(E)$ (in micrometres)

	L mm 10	110	250	510	590	690	1 010
$u(\varepsilon_{\text{cal}})$	0,26	0,31	0,38	0,51	0,55	0,60	0,76
$u(\varepsilon_{\alpha})$	—	—	—	—	—	—	—
$u(\varepsilon_{t})$	—	—	—	—	—	—	—
$u(\varepsilon_{\text{align}})$	0,08	0,08	0,08	0,08	0,08	0,08	0,08
$u(\varepsilon_{\text{fixt}})$	0,58	0,58	0,58	0,58	0,58	0,58	0,58
$u(E)$	0,64	0,66	0,69	0,77	0,80	0,83	0,95
$U(E)$	1,27	1,32	1,39	1,54	1,60	1,67	1,91
	NOTE $U(E) = k \times u(E)$, a coverage factor $k = 2$ is used.						



Key

X size, L, expressed in millimetres, of the material standard being measured

Y error of indication, E, expressed in micrometres

Figure C.2 — Final graphical representation of the MPE$_E$ and of the test uncertainties

The test uncertainties range now from 14 % to 31 % of the MPE$_E$ and may be considered adequate for the test.

C.3 Example 2

C.3.1 General

A high accuracy CMM in an air-conditioned laboratory is tested for acceptance using a ceramic test sphere and a set of steel gauge blocks. The specifications of the CMM and of the equipment used are reported in Table C.6; they are taken from the CMM data sheet and from the calibration certificates of the test sphere and of the gauge blocks. The value of the CTE is that recommended by the manufacturer of the gauge blocks.

Table C.6 — Specification of the CMM and of the equipment used

CMM	Measuring volume	(1 000 × 900 × 650) mm^3
	MPE_P	0,6 µm
	MPE_E	± (0,5 + L / 750) µm
	Thermally compensated with embedded thermometers	
	Proportional probing system with nearly zero force extrapolation	
Test sphere	Calibrated form error, F	(0,07 ± 0,1) µm
Gauge blocks	Calibration uncertainty of the size	0,1 µm + 0,25 × 10^{-6} × L
	CTE	(10,9 ± 0,35) × 10^{-6} K^{-1}
	Grade 0	

C.3.2 Test of probing error

The value of $u(F)$ is derived from the certificate as

$$u(F) = \frac{U(F)}{k} = \frac{0{,}1\,\mu\text{m}}{2} = 0{,}05\ \mu\text{m} \qquad \text{(C.9)}$$

The uncertainty $u(P)$ is evaluated by the equation

$$u(\varepsilon_{\text{form}}) = \sqrt{\left(\frac{F}{2}\right)^2 + u^2(F)} \qquad \text{(C.10)}$$

which in this case amounts to

$$u(P) = \sqrt{\left(\frac{0{,}07\ \mu\text{m}}{2}\right)^2 + (0{,}05\ \mu\text{m})^2} = 0{,}06\ \mu\text{m} \qquad \text{(C.11)}$$

With a coverage factor $k = 2$, the test uncertainty is

$$U(P) = k \times u(P) = 2 \times 0{,}06\ \mu\text{m} = 0{,}12\ \mu\text{m} \qquad \text{(C.12)}$$

This amounts to 20 % of the MPE_P, which may be considered adequate for the test.

C.3.3 Test of size

C.3.3.1 General

The shortest gauge block is taken to be 30 mm in length (see ISO 10360-2:2001, 5.3.2.1). As the spatial diagonal of the working volume is 1 494 mm, the longest gauge block shall not be shorter than 986 m, so a 1 000 mm gauge block is used. As this size is larger than the CMM travel in y and z, additional intermediate gauge blocks are used to fit the different travels. The resulting combination of lengths and their associated calibration uncertainties is given in Table C.7.

Table C.7 — Selection of gauge blocks used and their calibration uncertainties

L, mm	30	125	250	500	600	700	1 000
$U(\varepsilon_{\text{cal}})$, µm	0,11	0,13	0,16	0,23	0,25	0,28	0,35

The uncertainty $u(E)$ is evaluated by the equation

$$u(E) = \sqrt{u^2(\varepsilon_{\text{cal}}) + u^2(\varepsilon_{\alpha}) + u^2(\varepsilon_t) + u^2(\varepsilon_{\text{align}}) + u^2(\varepsilon_{\text{fixt}})} \quad \text{(C.13)}$$

NOTE The test uncertainties of the measurements of each size can vary with location and orientation, e.g. due to different thermal or fixturing uncertainty components. For simplicity, this is assumed not to be the case in this particular example.

C.3.3.2 Uncertainty due to the calibration of the material standards of size, $u(\varepsilon_{\text{cal}})$

This component is taken from the calibration certificate, dividing the reported value by the coverage factor, $k = 2$. The resulting values are given in Table C.8.

Table C.8 — Values of $u(\varepsilon_{\text{cal}})$ for the gauge blocks used

L, mm	30	125	250	500	600	700	1 000
$u(\varepsilon_{\text{cal}})$, µm	0,05	0,07	0,08	0,11	0,13	0,14	0,18

C.3.3.3 Uncertainty due to the CTE of the material standards of size, $u(\varepsilon_{\alpha})$

This component needs to be included, as the CMM is thermally compensated and user input of the numerical value of the CTE is required ($10{,}9 \times 10^{-6}$ K^{-1} in this case).

The uncertainty, $u(\varepsilon_{\alpha})$, is evaluated by the equation

$$u(\varepsilon_{\alpha}) = L \times (|t - 20\ °\text{C}|) \times u(\alpha) \quad \text{(C.14)}$$

The temperature range of the material standard of size during the test is between 20,31 °C and 20,78 °C. The value of $|t - 20$ °C$|$ in the above equation is taken as the largest in the range, i.e. $|t - 20$ °C$| = 0{,}78$ °C.

NOTE In principle, this value is valid only for the measurement when it occurs, and is smaller for the others. For simplicity, the resulting overestimation is included at this stage, but can be reconsidered after the test uncertainty, $U(E)$, has been evaluated, if it is considered too large (iterative approach of the PUMA method, see ISO/TS 14253-2).

The value of $u(\alpha)$ is taken from the recommendation of the gauge block manufacturer, dividing the reported value by the coverage factor $k = 2$.

The resulting values of the uncertainty $u(\varepsilon_{\alpha})$ are given in Table C.9.

Table C.9 — Values of $u(\varepsilon_{\alpha})$ for the gauge blocks used

L, mm	30	125	250	500	600	700	1 000
$u(\varepsilon_{\alpha})$, µm	0,00	0,02	0,03	0,07	0,08	0,10	0,14

C.3.3.4 Uncertainty due to the input temperature of the material standards of size, $u(\varepsilon_t)$

As the CMM is equipped with its own thermometers, this component is not considered.

C.3.3.5 Uncertainty due to misalignment of the material standard of size, $u(\varepsilon_{\text{align}})$

The alignment procedure is chosen to be consistent with the definition of the calibrated size, i.e. the central length, l_c, as defined in ISO 3650. A workpiece reference frame is set with an axis normal to a measuring face, and the actual point-to-point distance is taken as the difference of coordinates along this axis. When used as a datum, the measuring face is probed as far as possible from its centre. The alignment procedure is repeated for individual gauge blocks, even if the whole set used is mounted together for convenience of fixturing.

NOTE 1 In practice, the CMM software might need an additional orientation about the first axis, and the location of the origin in the plane of the measuring face, in order to set a fully defined workpiece reference frame, which would usually be based on lateral faces. This is not considered here, as it is irrelevant to the test uncertainty.

The uncertainty, $u(\varepsilon_{\text{align}})$, is evaluated by the equation

$$u\left(\varepsilon_{\text{align}}\right) = \sqrt{u^2\left(e_{\cos}\right) + u^2\left(e_{\text{parall}}\right)} \qquad \text{(C.15)}$$

The input values needed to evaluate $u(e_{\cos})$, are estimated as follows.

— A value of $L_{\text{align}} = 6$ mm is taken, as this is the distance between the alignment points along the shortest side of the measuring face. The shortest side is 9 mm (see ISO 3650), but an edge allowance is made to avoid the chamfers.

— As the actual value in the test on the probing error is $P = 0{,}45$ µm, a value of $u(p) = P/\sqrt{12} = 0{,}13$ µm is used.

— A value of $u(p_{\text{geo}}) = 0$ is taken, as the alignment is done following the definition of the calibrated size of the material standard of size axis.

The resulting value of $u(e_{\cos})$ is

$$u\left(e_{\cos}\right) = 2\sqrt{2} \times \frac{u^2(p) + u^2\left(p_{\text{geo}}\right)}{L_{\text{align}}^2} L = 2\sqrt{2} \times \frac{(0{,}13\ \mu\text{m})^2}{(6\ \text{mm})^2} L \approx 0 \qquad \text{(C.16)}$$

where the very accurate probing system makes the cosine error negligible.

The tolerance of the variation of length, t_v, varies from 0,1 µm to 0,4 µm for grade 0 gauge blocks, according to the size (see ISO 3650). The uncertainty, $u(e_{\text{parall}})$, is derived as $u(e_{\text{parall}}) = t_v/\sqrt{12}$. The resulting values are given in Table C.10.

Table C.10 — Values of $u(e_{\text{parall}})$ for the gauge blocks used

L, mm	30	125	250	500	600	700	1 000
t_v, µm	0,10	0,14	0,16	0,25	0,25	0,30	0,40
$u(e_{\text{parall}})$, µm	0,03	0,04	0,05	0,07	0,07	0,09	0,12

NOTE 2 These values of $u(p)$ and $u(e_{\text{parall}})$ are overestimated, as P is derived from multi-directional measurements, and t_v accounts for the full area of the measuring face while the portion involved in the measurement is smaller. The overestimation of $u(p)$ is negligible in this case, and that of $u(e_{\text{parall}})$ is included at this stage for simplicity, but this may be reconsidered after the test uncertainty $U(E)$ has been evaluated, if the results are too large (iterative approach of the PUMA method, see ISO/TS 14253-2).

C.3.3.6 Uncertainty of fixturing the material standard of size, $u(\varepsilon_{\text{fixt}})$

Each gauge block is fixtured at its Airy points (marked on the side faces) with symmetrical clamping devices, which impose only transverse stresses to the gauge block. No bending is expected to occur. The final clamping is done after a suitable settling time, to protect the fixturing from thermally-induced stresses.

The test described in A.3.2.6 is carried out to detect any rocking. As the actual probing measurement occurs at near zero force, the only relevant effect is the hysteresis, and the force is generated simply by the probing system, while probing the measuring face opposite to the dial gauge. The readings of the dial gauge are ΔL_{p1} = 0,04 µm and ΔL_{p2} = 0,03 µm, resulting in a value of $u(\varepsilon_{\text{fixt}}) = |\Delta L_b - (|\Delta L_{p1}| + |\Delta L_{p2}|)|$ = 0,07 µm.

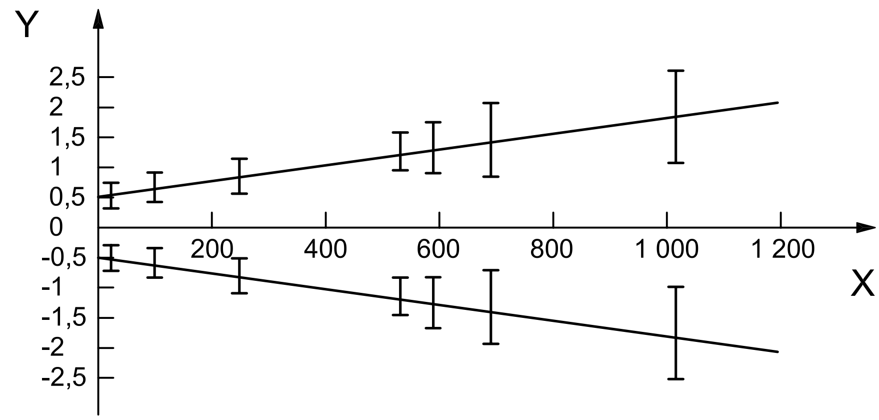
C.3.3.7 Final budget and graphical presentation of the test uncertainty, $u(E)$

Combining the above contributors results in the test uncertainty budget in Table C.11.

Table C.11 — Final budget of the test uncertainty, $u(E)$ (in micrometres)

	L mm						
	30	125	250	500	600	700	1 000
$u(\varepsilon_{\text{cal}})$	0,05	0,07	0,08	0,11	0,13	0,14	0,18
$u(\varepsilon_{\alpha})$	0,00	0,02	0,03	0,07	0,08	0,10	0,14
$u(\varepsilon_t)$	—	—	—	—	—	—	—
$u(\varepsilon_{\text{align}})$	0,03	0,04	0,05	0,07	0,07	0,09	0,12
$u(\varepsilon_{\text{fixt}})$	0,07	0,07	0,07	0,07	0,07	0,07	0,07
$u(E)$	0,09	0,11	0,12	0,17	0,18	0,20	0,26
$U(E)$	0,19	0,21	0,24	0,33	0,36	0,40	0,52
	NOTE $U(E) = k \times u(E)$, a coverage factor $k = 2$ is used.						

The graphical representation of the MPE_E and of the test uncertainties is illustrated in Figure C.3.



Key

X size, L, expressed in millimetres, of the material standard being measured

Y error of indication, E, expressed in micrometres

Figure C.3 — Graphical representation of the MPE_E and of the test uncertainties

The test uncertainties range from 34 % of the MPE_E, for the shortest gauge block, down to 28 %, for the longest, and may be considered adequate for the test. However, these values are not optimal, particularly for short sizes. To improve this, the large value of the misalignment component could be reduced by a more careful evaluation, e.g. by considering that the portion of measuring face actually involved in the test is smaller than the measuring face itself (see C.3.3.5).

Annex D
(informative)

Relation to the GPS matrix model

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

D.1 Information about the standard and its use

This Technical Specification provides guidance for applying the test of ISO 10360-2, by explaining the evaluation of the test uncertainty required for ISO 14253-1.

D.2 Position in the GPS matrix model

This Technical Specification belongs to the general GPS series of documents, and influences chain link 5 of the chains of standards on size, distance, radius, angle, form, orientation, location, run-out and datums in the general GPS matrix, as graphically illustrated on Figure D.1.

Fundamental GPS standards

Global GPS standards

General GPS standards						
Chain link number	**1**	**2**	**3**	**4**	**5**	**6**
Size						
Distance						
Radius						
Angle						
Form of line independent of datum						
Form of line dependent of datum						
Form of surface independent of datum						
Form of surface dependent of datum						
Orientation						
Location						
Circular run-out						
Total run-out						
Datums						
Roughness profile						
Waviness profile						
Primary profile						
Surface imperfections						
Edges						

Figure D.1 — Position in the GPS matrix model

D.3 Related standards

The related standards are those of the chains of standards indicated in Figure D.1.

Bibliography

[1] ISO/TR 14638:1995, *Geometrical product specification (GPS) — Masterplan*

[2] ISO/TR 16015:2003, *Geometrical product specifications (GPS) — Systematic errors and contributions to measurement uncertainty of length measurement due to thermal influences*

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