



Technical Specification

ISO/TS 15530-2

Geometrical product specifications (GPS) — Coordinate measuring machines (CMM): Technique for determining the uncertainty of measurement —

Part 2: Use of multiple workpiece orientations and calibrated simple standards

Spécification géométrique des produits (GPS) — Machines à mesurer tridimensionnelles (MMT) : Technique pour la détermination de l'incertitude de mesure —

Partie 2: Utilisation de plusieurs orientations de la pièce et d'étalons simples étalonnés

**First edition
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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.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO document should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

ISO draws attention to the possibility that the implementation of this document may involve the use of (a) patent(s). ISO takes no position concerning the evidence, validity or applicability of any claimed patent rights in respect thereof. As of the date of publication of this document, ISO had not received notice of (a) patent(s) which may be required to implement this document. However, implementers are cautioned that this may not represent the latest information, which may be obtained from the patent database available at www.iso.org/patents. ISO shall not be held responsible for identifying any or all such patent rights.

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

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

A list of all parts in the ISO 15530 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

This document is a geometrical product specification (GPS). It influences chain link G of the chain of standards on size, distance, form, orientation, location and run-out in the general GPS matrix (see [Annex F](#)).

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

For more detailed information on the relation of this document to the GPS matrix model, see [Annex F](#).

Coordinate measuring systems (CMS) have become essential for verifying geometrical specifications in industry. According to the ISO 9000 series of standards, in a quality management system, the relevant measuring equipment is required to be calibrated against certified equipment having a known and valid relationship to internationally or nationally recognized standards, in order to establish traceability. According to ISO/IEC Guide 99, the *International vocabulary of basic and general terms in metrology* (VIM), a calibration comprises – besides the establishment of the relationship between the measured and the correct values of a quantity – the uncertainty evaluation in the final results (measurands) of the measurement task. However, evaluating the uncertainty for the numerous measurement tasks a CMS performs is often very complex. In these cases, the risk of an unrealistic estimation of task-related uncertainty is likely to arise.

The aim of this document is to provide a method and related procedures for the evaluation of the measurement uncertainty of specific measuring tasks using CMS. The method applies to Cartesian coordinate measuring machines (CMM) equipped with tactile probing systems. This method can possibly be applied to other CMS, however the difference in CMS kinematics and appropriate error model must be considered. This is not a trivial effort to investigate what measurement orientations can randomize systematic errors using that CMS. This document is a Technical Specification, and as such, feedback is sought regarding its usage and performance within its scope (i.e., on contact Cartesian CMM). It is expected that various investigations will take place on other types of CMS. As these investigations can occur (perhaps with adaptations of the method to the particular CMS technology, e.g., kinematics), feedback is welcome regarding these other technologies as well.

A possible application of the method described in this document is the calibration of workpieces. The workpiece and the related calibration results can be utilized as "calibrated workpieces" in ISO 15530-3. The calibration values and their calibration uncertainties are derived by this document.

Another possible application is the conformity verification of workpieces against their geometrical specifications in accordance with ISO 14253-1 or ISO/TR 14253-6. The method described in this document provides the values and uncertainties of the specified geometrical characteristics, which are used as the test values and guardbanding.

Another possible application is the estimation of the task-specific measurement uncertainty (see ISO/TS 15530-1) within the PUMA method in ISO 14253-2, whereby a CMM user can compare different measurement conditions, e.g. fewer measurement repetitions.

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Geometrical product specifications (GPS) — Coordinate measuring machines (CMM): Technique for determining the uncertainty of measurement —

Part 2:

Use of multiple workpiece orientations and calibrated simple standards

1 Scope

This document describes a procedure for the evaluation of the uncertainty of measurements made with tactile Cartesian coordinate measuring machines (CMM).

The measurement uncertainty evaluated in accordance with this document indicates the performance of the individual measurement operation, which is not the measuring capability nor test uncertainty when verifying the performance of the CMM against its maximum permissible errors (MPE).

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 1101, *Geometrical product specifications (GPS) — Geometrical tolerancing — Tolerances of form, orientation, location and run-out*

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

ISO/TS 15530-1, *Geometrical product specifications (GPS) — Coordinate measuring machines (CMM): Technique for determining the uncertainty of measurement — Part 1: Overview and metrological characteristics*

ISO/IEC Guide 99, *International vocabulary of metrology — Basic and general concepts and associated terms (VIM)*

ISO/IEC Guide 98-3, *Uncertainty of measurement — Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 1101, ISO 10360-1, ISO/TS 15530-1, ISO/IEC Guide 99, ISO/IEC Guide 98-3 and the following apply.

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

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <https://www.electropedia.org/>

3.1 nominal sampling pattern

measurement points in an agreed upon pattern extracted from the workpiece and used to associate one or more characteristics of interest

Note 1 to entry: The nominal sampling patterns are essential parts of the measurand definitions, and their designation is to be stated clearly e.g. in the measurement protocols.

3.2 undetected uncertainty contribution

uncertainty contribution not detected by the described usage of multiple workpiece orientations and calibrated simple standards

Note 1 to entry: Undetected uncertainty contributors are discussed in [Annex E](#).

4 Symbols

For the purpose of this document, the symbols given in [Table 1](#) apply.

Table 1 — Symbols

Symbol	Definition
$u(y_{\text{result}})$	standard uncertainty of the final corrected result of the measurement
$U(y_{\text{result}})$	expanded uncertainty of the final corrected result of the measurement
k	coverage factor for calibration use
i	index for the current measurement in a series of repeated measurements
j	index for the current workpiece orientation, or, index for the probe stylus
h	index for the measurement point ID in the nominal sampling pattern, or, index for the length standard
n_{WR}	number of repeated measurements of the workpiece in a single orientation, where W stands for workpiece and R stands for repeated measurements
n_{WO}	number of workpiece orientations, where W stands for workpiece and O stands for orientations of the workpiece
n_{LR}	number of repeated measurements of a length standard in a single orientation, where L stands for length standard and R stands for repeated measurements
n_{LO}	number of length standard orientations, where L stands for length standard and O stands orientations of the length standard
n_{LN}	number of length standard(s) measured in a single orientation, where L stands for length standard and N stands for the number of length standard(s)
n_{PR}	number of repeated measurements of a probe verification standard with a single stylus, where P stands for probe stylus and R stands for repeated measurements
n_{PO}	number of probe styli orientations to be used, where P stands for probe stylus and O stands for orientation of the probe stylus
n_{MP}	number of measurement points in a nominal sampling pattern, where M stands for measurement and P stands for points
y_{ij}	measured value; workpiece orientation j ($1 \leq j \leq n_{WO}$), repetition i ($1 \leq i \leq n_{WR}$)
y_{ijh}	measured value at the h -th point on the workpiece ($1 \leq h \leq n_{MP}$); workpiece orientation j ($1 \leq j \leq n_{WO}$), repetition i ($1 \leq i \leq n_{WR}$)
w_{ij}	measured value for the calibration/test; workpiece orientation j ($1 \leq j \leq n_{OW}$), repetition i ($1 \leq i \leq n_{WR}$)
y_{result}	calibration/test result value of the feature
y	raw measurement result, not corrected for the bias
W	raw measurement value for the calibration/test
y_{corr}	measurement result corrected for the bias
E_S	average scale error of the CMM in the region of interest

Table 1 (continued)

Symbol	Definition
$L_{\text{Meas.}ij}$	measured value of the length standard; orientation j ($1 \leq j \leq n_{L0}$), repetition i ($1 \leq i \leq n_{LR}$)
$L_{\text{Meas.}ijh}$	measured value of the h -th length standard ($1 \leq h \leq n_{LN}$); orientation j ($1 \leq j \leq n_{L0}$), repetition i ($1 \leq i \leq n_{LR}$)
u_S	standard uncertainty attributed to the scale error
E_D	average error of the probe size qualification
$D_{\text{Meas.}ij}$	measured value of the diameter of the probe verification standard; stylus j ($1 \leq j \leq n_{p0}$), repetition i ($1 \leq i \leq n_{pR}$)
u_D	standard uncertainty attributed to the probe size error
E_{PrbLoc}	average error of the probe location qualification
$D_{\text{MCS.}i}$	diameter of the minimum circumscribed sphere enclosing the centres of the least-square spheres of the probe verification standard measured with the n_{p0} probe styli; repetition i ($1 \leq i \leq n_{pR}$)
u_{PrbLoc}	standard uncertainty attributed to the probe location error
$u_{\text{WR}}(Y)$	standard uncertainty attributed to the repeatability of the workpiece measurement
$u_{\text{W0}}(Y)$	standard uncertainty attributed to the randomized systematic errors of the CMM geometry and environment
$u_{\text{W0} \times \text{dist}}(Y)$	standard uncertainty attributed to the interaction between the error of the CMM geometry and environment, and the measurement points in the nominal sampling pattern on the feature element
u_{temp}	standard uncertainty attributed to temperature-related effects
u_{UUC}	uncertainty contributor which is undetected by the method described in this document, and have been evaluated by other appropriate methods

5 Requirements for uncertainty assessment

The method requires that the measurement for each geometrical feature is performed with the nominal sampling pattern of the measurement points on the surface of the geometrical feature. Defining the number of the measurement points and the sampling scheme are parts of measurement strategy design, therefore, they shall be selected to be suitable for the test purpose. This document specifies neither the default number of measurement points on the surface of the geometrical feature nor the default sampling pattern.

The number of points and their pattern (defined outside the scope of this document) are sources of measurement uncertainty, but those uncertainty components are not detected in this method and are discussed in [Annex E](#).

Likewise, the specification of the association, e.g., Gaussian or Chebyshev, is a part of the test protocol design, therefore, it is out of the scope of this document even though it can be a source of undetected measurement uncertainty. This document does not specify the association to be used. The initializations, conditions, and preliminary procedures applied – or that will apply – to the actual measurement of the workpiece shall be retained during the measurements to evaluate the uncertainty as described in this document.

NOTE 1 An example of a condition is whether and how the CMM compensates its geometry errors.

NOTE 2 Examples of preliminary procedures are the probe configuration and qualification.

6 Principle of measurement and uncertainty assessment

Essentially, a CMM measures single-point coordinates. The dimensions and geometrical deviations of the features are computed from the set of measurement points sampled by the CMM. Therefore, the uncertainty in the measured value of the dimensions or geometrical deviations is derived from the uncertainty of each single point coordinates. This is a combination of various uncertainty contributors, which are difficult to evaluate individually because of the complexity of a CMM measurement task.

In practice, combined uncertainties of measurements are dominated by random errors and systematic errors. When a workpiece is measured on a CMM in one orientation, the measured coordinates of a single

point in the workpiece coordinate system include random and systematic errors. The errors derived from the contributors are propagated to the machine coordinates of the CMM. The contributions of these factors to the measurement uncertainty propagate and are categorized into components, such as the items listed in an uncertainty budget.

If a measurement is made in a fixed orientation and environment, then, the measurement result is biased by systematic errors. Even if the measurement is repeated and the measurement results are averaged, the bias incurred by the orientation and environment is neither eliminated nor reduced. To eliminate or reduce the effect of the bias and to evaluate the magnitude of it, extra independent measurements are necessary (see Annex E.3).

Proper experimental design can help reduce the impact of unknown systematic errors by randomizing them. One effective approach is to use multiple measurement techniques. Different instruments or environmental conditions introduce unique systematic errors. When combined, these errors vary across measurements, making them appear more like random errors. This approach mitigates the influence of systematic bias and improves the accuracy of the results.

In the procedure of this document, a workpiece is measured in different orientations on a CMM. This approach randomizes the contribution of many systematic errors in the respective measurements by varying the magnitude and coefficient of the error propagation to the measured results. The systematic error that occurs in CMM measurement is autocorrelated with the position and orientation of the measured workpiece on the CMM, which means the points nearby have similar systematic errors. This autocorrelation decreases with the distance from the original position and orientation. The effect of this systematic error is assumed to follow a normal distribution with an expected value of zero and a standard deviation of $u_{W0}(y)$. The effect of the systematic error is then ideally neutralized by averaging the measurement results in different orientations chosen for the randomization and becomes a randomized systematic error.

NOTE Some systematic errors are possibly not sufficiently randomized, such as those caused by fixturing, see Annex E.

The contributions of random errors and systematic errors in multi-orientation measurements are evaluated using two-way repeated measures analysis of variance (referred to as ANOVA in this document). ANOVA separates the total variance into components attributed to distinct factors, such as random and systematic sources, without double counting. This method helps identify critical sources of measurement uncertainty by isolating their respective contributions.

Specifically, random errors correspond to the within-groups variance, while systematic errors are associated with the between-groups variance. Simple calculations of between-groups variance from raw measurement data inherently include within-groups variance, leading to double counting in uncertainty assessments. To address this, ANOVA isolates the between-groups variance, ensuring it represents only the contributions of systematic errors without overlap from random errors. This distinction is critical for accurate uncertainty quantification in measurement experiments.

Even with performing multi-orientation measurements, some systematic errors in CMM measurements are still not randomized. The dominant errors which are not randomized are the scaling error of the CMM and the probe qualification error. The respective effects of these errors are assessed, and if necessary, corrected. In addition, their contributions to the measurement uncertainty are evaluated, and included in the computation of the measurement uncertainty.

7 Procedure

7.1 Measurements

7.1.1 General

Figure 1 shows the flowchart of the operation described in this document. The overall measurement procedure consists of three steps:

- a) multiple measurements of the workpiece;

- b) measurements of length standards;
- c) measurements of a test sphere.

All measurements are carried out in the same portion of the CMM measuring volume.

The repetitive measurements in one orientation are performed without re-alignment.

The multiple measurements of the workpiece are performed by repetition with several workpiece orientations with the identical distribution of probing points and the identical measurement strategy. This procedure is intended to randomize the systematic errors of the CMM including environmental fluctuation surrounding the CMM.

The measurements of length standards – such as a gauge block – are executed with the standard in three directions perpendicular to one another, typically along the X, Y and Z axes of the CMM. This procedure is intended to capture the CMM scale errors, including thermal effects. The length standard should be measured near or at the position of the workpiece.

The measurements of a test sphere are executed with all probe styli used for the previous steps and applying the same probing mode(s) as used for the previous steps. This procedure is intended to investigate the probing errors.

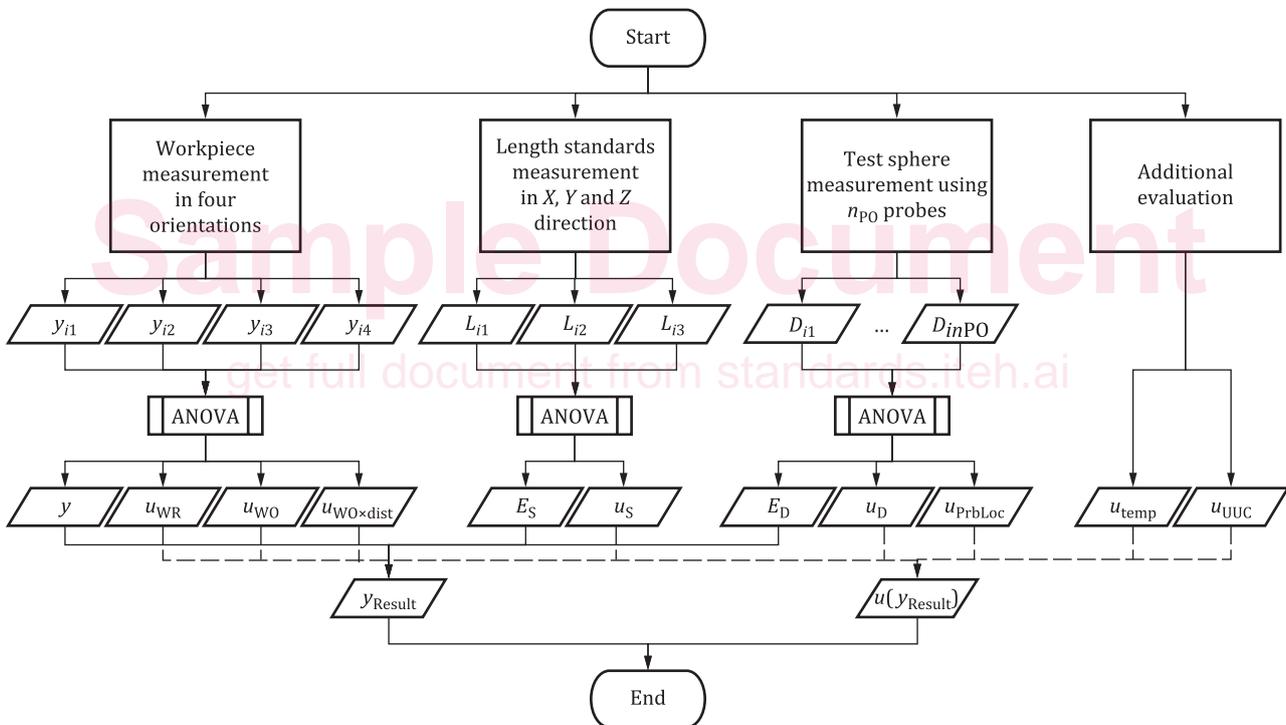


Figure 1 — Flowchart of the operation procedure

7.1.2 Multiple measurements on the workpiece

The workpiece is measured in four orientations as a default. Measurements in more orientations may be performed to better randomize systematic effect. Figure 2 shows an example of the measurement setup of a workpiece on the CMM. One orientation is referred to as the "home position". The others are example orientations to randomize the systematic effects of the CMM.

To avoid a biased result, and to avoid the underestimation of the measurement uncertainty, the variety of orientations of the workpiece shall be considered carefully. An insufficient variety of workpiece orientations can fail to randomize the systematic effect of the CMM. This can result in unknown and uncompensated biases being present in the calibration/test results, leading to an underestimation of measurement uncertainty.

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The workpiece orientation shall be chosen within the rated test conditions of the workpiece measurement. Other than the home position, three orientations are recommended, obtained by rotating the artefact at home position 90° in turn about the first CMM axis, obtained by rotating the artefact at home position 90° in turn about the second CMM axis and obtained by rotating the artefact at home position 90° in turn about the third CMM axis.

When the orientation of the workpiece against the direction of gravitational force is specified as a part of test protocol, any orientation for the measurement shall satisfy the specification.

The measurements are carried out with an identical distribution of measured points (the same sampling pattern) and with an identical measurement strategy, i.e. the number and nominal locations of the measured points for extraction (see ISO 14406) and as well the probing strategy and the data point analysis (e.g. filtering) are the same for all orientations. In the case that the method applies to calibration of the workpiece, the actual distribution of the measured points shall be recorded.

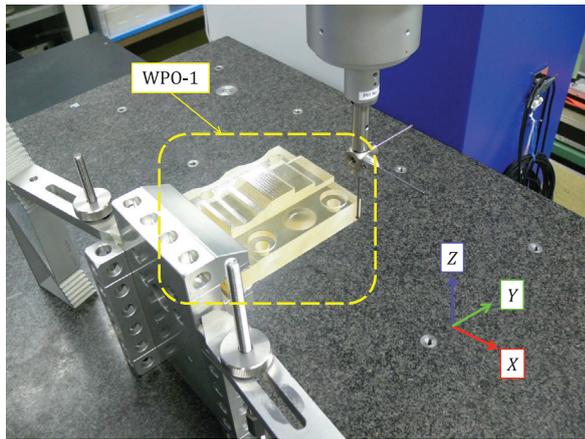
The number of repetitions for each orientation is three by default.

When a CMM is known to have poor repeatability, e.g. the CMM exhibited a large R_0 value in its acceptance/reverification test or is specified with a large $R_{0,MPE}$ value according to ISO 10360-2, the number of repetitions may be increased at the discretion of the CMM user. For example, the CMM user chose the appropriate number of repetitions against the measurement purpose by PUMA process (see ISO 14253-2).

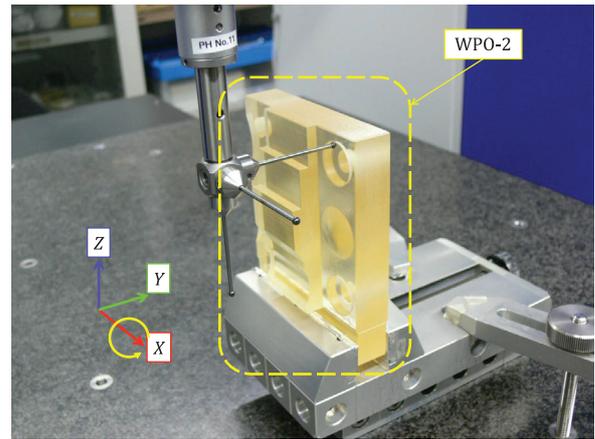
Ideally the mounting method of the workpiece should be identical for each of the four orientations. But due to the shape of the workpiece the mounting method of the workpiece, e.g. clamping, may be required to be different. In order to perform a valid measurement series, the following aspects shall be controlled:

- a) The workpiece deformation due to mounting shall be considered and, likewise, controlled.
- b) Uncontrolled and exaptational workpiece deformation can be the source of additional measurement uncertainty contributors, especially if the deformations are strong and different between orientations.

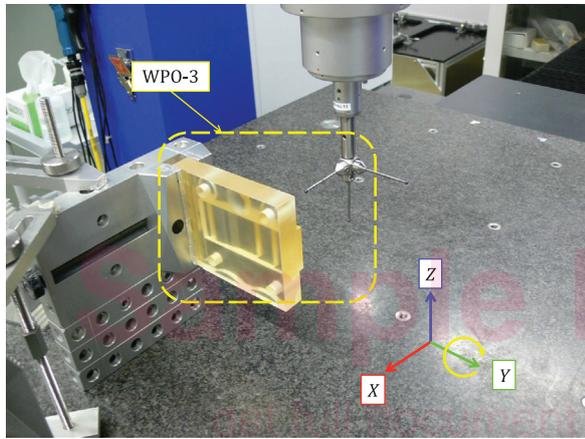
The results of all these measurements are the values y_{ij} (see [Table 2](#)), where $j = 1 \dots n_{WO}$ indicates the orientation and $i = 1 \dots n_{WR}$ indicates the repeat within the same orientation.



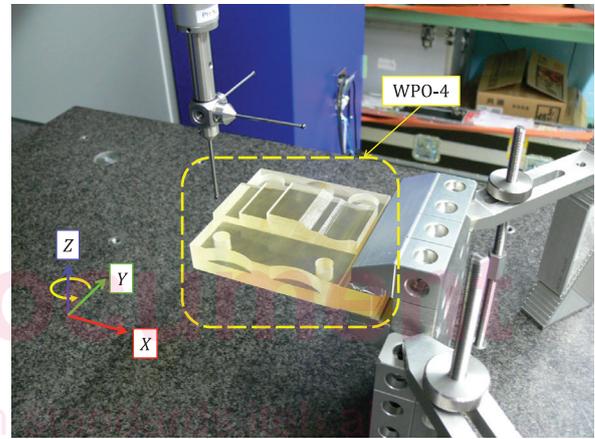
a) Orientation 1
(home position)



b) Orientation 2
(Example: 90° rotated from home position about the first axis of the CMM)



c) Orientation 3
(Example: 90° rotated from home position about the second axis of the CMM)



d) Orientation 4
(Example: 90° rotated from home position about the third axis of the CMM)

Key

- X X-axis of the coordinate system on the CMM
- Y Y-axis of the coordinate system on the CMM
- Z Z-axis of the coordinate system on the CMM
- WPO-*i* (*i* = 1, 2, 3, 4) workpiece in orientation-*i*

Figure 2 — Example of measurement setup of the workpiece in four orientations

Table 2 — Summary of measurement results of the workpiece

	Orientation 1 (home position)	Orientation 2	Orientation 3	Orientation 4
Repeat 1	y_{11}	y_{12}	y_{13}	y_{14}
Repeat 2	y_{21}	y_{22}	y_{23}	y_{24}
Repeat 3	y_{31}	y_{32}	y_{33}	y_{34}

7.1.3 Measurements of standards of length

Material standards of length (or a single standard featuring multiple test lengths) are measured in the same portion of the CMM volume where the workpiece is measured. The results of the measurements of the length standards are used for two purposes:

- for the compensation of the scale error of the CMM in the region of interest when corrected, and
- for the evaluation of the uncertainty derived from that scale error.

The measurements of length standards are performed in at least three orientations to quantify the three-dimensional spatial scale error of the CMM in the portion of the CMM volume. The orientations are approximately orthogonal to each other, typically aligned to the CMM axes. [Figure 3](#) shows an example setup.

In each orientation, the length standards are measured at least three times.

NOTE When it is a priori known that the measurement repeatability of the CMM to be used is significantly large, the number of repetitions may be larger than the default number of three.

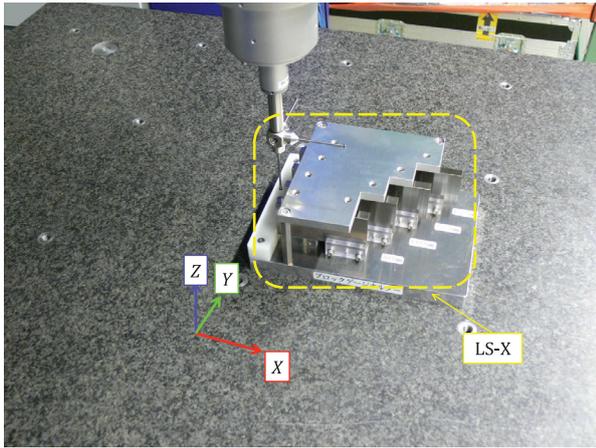
Results are the values $L_{\text{Meas},ij}$ in [Table 3](#) and [Table 4](#) with $j = 1 \dots n_{LO}$ indicating the orientation and $i = 1 \dots n_{LR}$ indicating the repetitions within the same orientation.

In the case the maximum size of the workpiece to be measured is small, or the purpose of the workpiece measurement is the acceptance test for that workpiece, the measurement using a single length standard may be sufficient even if the workpiece has multiple size features.

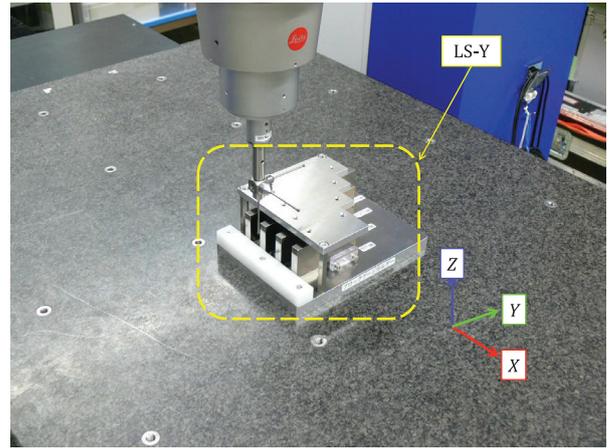
Ideally, the scale error values are detected without the influence of probing errors. Therefore, it is recommended to measure the length standards in a unidirectional manner (see ISO 10360-2:2009, Annex B) or E_{Vol} manner (see ISO 10360-13:2021, 3.12).

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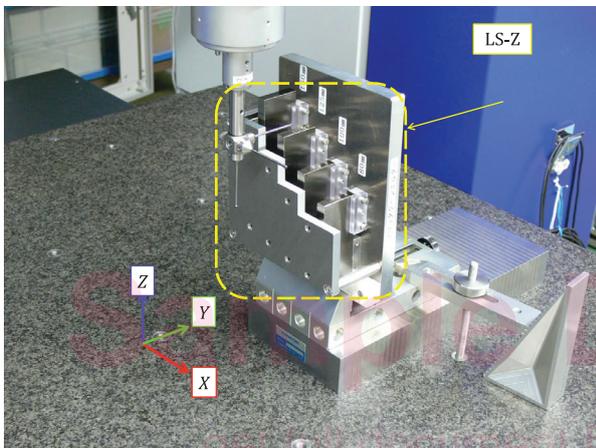
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a) Orientation 1
(Example: X axis direction)



b) Orientation 2
(Example: Y axis direction)



c) Orientation 3
(Example: Z axis direction)

Key

- X X-axis of the coordinate system on the CMM
- Y Y-axis of the coordinate system on the CMM
- Z Z-axis of the coordinate system on the CMM
- LS-*i* (*i* = X, Y, Z) length standards in direction of *i*

Figure 3 — Measurement setup of the length standard in three mutually orthogonal directions

Table 3 — Summary of measurement results of the length standard (for ANOVA)

	Orientation 1 (X axis direction)	Orientation 2 (Y axis direction)	Orientation 3 (Z axis direction)
Repeat 1	$L_{\text{Meas.11}}$	$L_{\text{Meas.12}}$	$L_{\text{Meas.13}}$
Repeat 2	$L_{\text{Meas.21}}$	$L_{\text{Meas.22}}$	$L_{\text{Meas.23}}$
Repeat 3	$L_{\text{Meas.31}}$	$L_{\text{Meas.32}}$	$L_{\text{Meas.33}}$