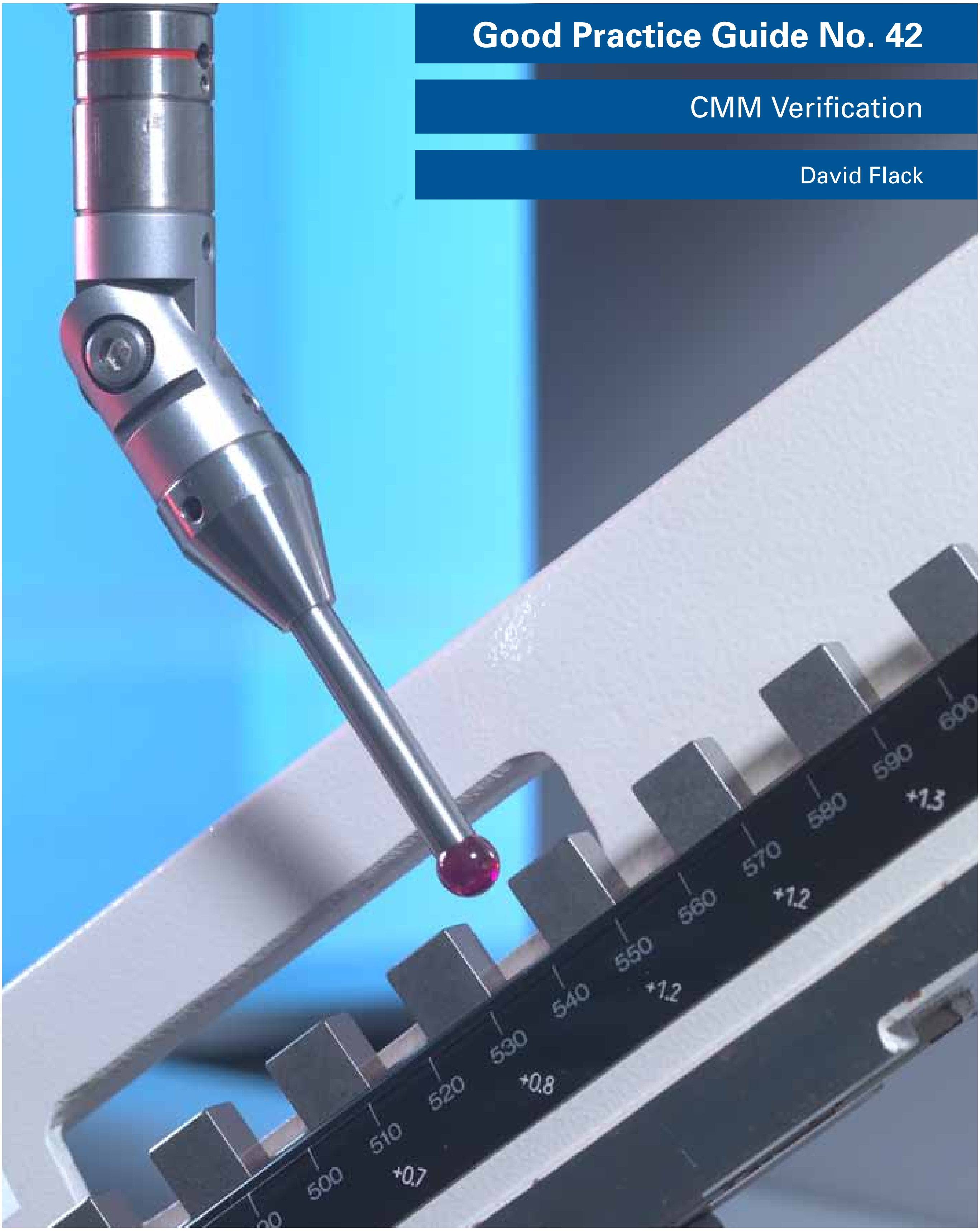
NPL
National Physical Laboratory

# Good Practice Guide No. 42

## CMM Verification

David Flack

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Measurement
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Issue 2

# Measurement Good Practice Guide No. 42

CMM Verification

David Flack

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ABSTRACT
This guide covers performance assessment of CMM accuracy, use of everyday artefacts for regular CMM checking, methods of monitoring machine performance between formal verification intervals and traceability. It is an update of a guide first published in 2001.

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## CMM Verification

# Preface

*The author hopes that after reading this Good Practice Guide you will be able to better understand the specifications relating to co-ordinate measuring machines. The content is written at a simpler technical level than many of the standard textbooks so that a wider audience can understand it. I am not trying to replace a whole raft of good textbooks, operator's manuals, specifications and standards, rather present an overview of good practice and techniques.*

"*Metrology is not just a process of measurement that is applied to an end product. It should also be one of the considerations taken into account at the design stage. According to the Geometrical Product Specification (GPS) model, tolerancing and uncertainty issues should be taken into account during all stages of design, manufacture and testing. The most compelling reason is that it is often considerably more expensive to re-engineer a product at a later stage when it is found that it is difficult to measure, compared to designing at the start with the needs of metrology in mind."* Professor Richard Leach 2003.

## GOOD MEASUREMENT PRACTICE

There are six guiding principles to good measurement practice that have been defined by NPL. They are:

**The Right Measurements:** *Measurements should only be made to satisfy agreed and well-specified requirements.*

**The Right Tools:** *Measurements should be made using equipment and methods that have been demonstrated to be fit for purpose.*

**The Right People:** *Measurement staff should be competent, properly qualified and well informed.*

**Regular Review:** *There should be both internal and independent assessment of the technical performance of all measurement facilities and procedures.*

**Demonstratable Consistency:** *Measurements made in one location should be consistent with those made elsewhere.*

**The Right Procedures:** *Well-defined procedures consistent with national or international standards should be in place for all measurements.*

# Introduction

# 1

**IN THIS CHAPTER**

- What this guide is about and what it is not
- Introduction to ISO 10360 and this guide
- Note on optical CMMs
- Non-Cartesian CMMs

This measurement good practice guide provides an overview of the ISO 10360 series of specification standards. It is an update to a guide first published in 2001 and has been updated to reflect changes in the standards over the last ten years.

## What this guide is about and what it is not

It is intended that this guide should give enough information so that the metrologist can interpret the requirements of the international standards relating to co-ordinate measuring machines. This guide will allow operators to interpret the results from third parties who have verified their machine. It will also provide information to allow more advanced users to carry out the tests themselves. This good practice guide is not intended to be an authoritative guide to the standards and the primary reference should always be the standards themselves.

## Introduction to ISO 10360 and this guide

### *Co-ordinate measuring machines*

International standard ISO 10360-1 defines a co-ordinate measuring machine (CMM) as a measuring system with the means to move a probing system and capability to determine spatial coordinates on a workpiece surface. Over the years, standards and guidelines have been developed to harmonize the performance specifications of a CMM to enable a user to make meaningful performance comparisons when purchasing a machine and, once purchased, to provide a well-defined way in which the specified performance can be verified.

For the user, demonstrating traceability to national standards and estimating the accuracy of measurements made with three dimensional CMMs is of importance for maintaining confidence and reliability in the measurements.

The ISO 10360 series of standards detail the acceptance, reverification tests and interim checks required to determine whether the CMM performs to the manufacturer's stated maximum permissible error of length measurement. However, even with these tests it is not possible to make a statement about the length measurement capability of the machine due to the complicated way in which the uncertainties associated with the CMM combine. Therefore, the length measurement uncertainty derived from a limited sample of measurements cannot be considered to be representative of all the possible length measurement tasks and certainly not of the measurement tasks the CMM is capable of performing. In effect the tests do not guarantee traceability of measurement for all measurement tasks performed. The user should be aware of this important fact and develop task-related measuring strategies for each measurement undertaken that will provide the appropriate level of confidence in the overall result. Virtual CMMs, for instance Pundit[1] and those in Calypso and Quindos can meet this requirement. Further information on virtual CMMs can be found in NPL report CMSC 01/00 *Simulated Instruments and Uncertainty Estimation* A B Forbes and P M Harris and ISO 15530-4 Geometrical product specifications (GPS). *Coordinate measuring machines (CMM). Technique for determining the uncertainty of measurement. Evaluating task-specific measurement uncertainty using simulation*.

[1] Website www.metrosage.com

***Structure of ISO 10360***

International Standard ISO 10360 covers CMM verification. This standard currently has six parts:

- ISO 10360-1: 2000 *Geometrical Product Specifications (GPS) – Acceptance and reverification tests for coordinate measuring machines (CMM) — Part 1: Vocabulary*
- ISO 10360-2: 2009 *Geometrical product specifications (GPS) – Acceptance and reverification tests for coordinate measuring machines (CMM) — Part 2: CMMs used for measuring linear dimensions*
- ISO 10360-3: 2000 *Geometrical Product Specifications (GPS) – Acceptance and reverification tests for coordinate measuring machines (CMM ) — Part 3: CMMs with the axis of a rotary table as the fourth axis*
- ISO 10360-4: 2000 *Geometrical Product Specifications (GPS) – Acceptance and reverification tests for coordinate measuring machines (CMM) — Part 4: CMMs used is scanning measuring mode*
- ISO 10360-5 :2010 *Geometrical Product Specifications (GPS) – Acceptance and reverification tests for coordinate measuring machines (CMM) — Part 5: CMMs using multiple-stylus probing systems*
- ISO 10360-6 :2001 *Geometrical Product Specifications (GPS) – Acceptance and reverification tests for coordinate measuring machines (CMM) — Part 6: Estimation of errors in computing Gaussian associated features*

Part 2 and part 5 have been updated since the last revision of this guide. Part 6 has been added to this series of standards since this guide was last published.

This guide will concentrate on the tests listed in part 2 of the standard and will cover some aspects of parts 3 and 5.

It is suggested that the reader regularly checks the catalogue on the ISO web site for further information and to see when new standards are published.

In addition ISO/TS 23165: 2006 *Geometrical product specifications (GPS) – Guidelines for the evaluation of coordinate measuring machine (CMM) test uncertainty* provides guidance on how to calculate the uncertainty of measurement associated with the test.

## Note on optical CMMs

ISO 10360 does not explicitly apply to CMMs using optical probing, however, if, by mutual agreement, the ISO 10360 approach is applied to optical CMMs, then additional issues, such as the following, should be considered:

- in the case of two dimensional sensors (no ram movement), an index 2D may be used for indication, *e.g.* $E_{0\text{-}2D}$;
- in the case of two dimensional systems, the number and location of the measurement positions may be reduced;
- specifications for the magnification and illumination;
- artefact issues such as material and surface finish that affect the test results; and

- bidirectional probing may or may not be possible depending on the artefact and probing system.

The following parts of the standard are currently under development as of April 2011:

ISO 10360-7 *Geometrical product specifications (GPS) – Acceptance and reverification tests for coordinate measuring machines (CMMs) – Part 7: CMMs equipped with imaging probing systems*

ISO/CD 10360-8 *Geometrical product specifications (GPS) – Acceptance and reverification tests for coordinate measuring machines (CMM) – Part 8: CMMs with optical distance sensors*

ISO/DIS 10360-9 *Geometrical product specifications (GPS) – Acceptance and reverification tests for coordinate measuring machines (CMM) – Part 9: CMMs with multiple probing systems*

## Non-Cartesian CMMs

ISO 10360-2 does not explicitly apply to non-Cartesian CMMs, however, it may be applied to non-Cartesian CMMs by mutual agreement.

Work is on-going within the relevant ISO technical committee (ISO/TC 213) on the document ISO 10360-10 *Geometrical Product Specifications (GPS) – Acceptance and reverification tests for coordinate measuring systems (CMS) – part 10: Laser trackers for measuring point-to-point distances*.

Work is also under way in developing international standards for articulated arm CMMs (AACMMs).

# Sources of CMM Error

# 2

**IN THIS CHAPTER**

- An Introduction to CMM error sources
- ISO 10360 and CMM errors

The purpose of chapter 2 is to give the reader an introduction to the error sources in CMM measurement. Other sources of information will give you are more detailed account of CMM error sources but the following aims to give the reader some background information to better appreciate the ISO 10360 series of specification standards.

## An introduction to CMM error sources

Sources of errors in CMM measurements can be classified as spatial errors or computational errors. Spatial errors are errors in the measured position of a point on the surface of the workpiece and are determined by:

- the accuracy of the components of the CMM - the guideways, the scales, the probe system and the qualification sphere;
- the environment in which the CMM operates - the ambient temperature, temperature gradients, humidity and vibration;
- the probing strategy used – the magnitude and direction of the probe force, the type of probe stylus used and the measuring speed of the probe; and
- the characteristics of the workpiece – elasticity, surface roughness, hardness and the mass of the component.

Computational errors are the errors in the estimated dimensions and form deviations of the workpiece and are determined by:

- the CMM software used to estimate the geometry of the workpiece;
- the precision of the computer used on the CMM;
- the number and relative position of the measured points; and
- the extent to which the geometry departs from the ideal geometric form.

Geometric errors of a CMM are either measured directly using laser interferometers and specialist optics, such as those from a number of commercial suppliers or indirectly using sequential multi-lateration using, for instance, the Etalon LaserTRACER. Once measured these errors may be used to error correct the machine (computer-aided accuracy or CAA).

**CMM geometric errors?**

A CMM has twenty-one sources of kinematic error. Kinematic errors are errors in the machine components due to imperfect manufacturing or alignment during assembly. The straight-line motion of a moving component always involves six components of deviation from the nominal path:

a) one positional deviation, in the direction of motion (linearity);
b) two linear deviations orthogonal to the direction of motion (straightness);
c) three angular deviations (rigid body rotations - roll, pitch and yaw).

In addition there are the three squareness errors between pairs of axes.

# ISO 10360 and CMM errors

CMM performance verification guidelines and tests are based on sampling the length-measurement capability of the instrument to determine whether its performance conforms to the manufacturer's stated maximum permissible error of length measurement (see Maximum permissible error of indication of a CMM for size measurement). The tests only allow a statement to be made about the overall length-measurement capability of the CMM. This limitation is due to the complicated way in which errors combine within a CMM. Therefore, the sampled length-measurement uncertainty cannot be considered to be representative of all the possible measurement tasks the CMM is capable of performing.

**Calibrate or verify?**

Three terms that are often confusingly interchanged when talking about CMMs are the terms *qualification, verification* and *calibration*. CMM operators often erroneously talk about calibrating the probe or getting the CMM calibrated to ISO 10360. To avoid confusion the correct terms are listed below.

**Stylus/Probing system qualification** – A task carried out day-to-day to determine the effective radius of the stylus tip.

**CMM verification** – A task carried out at periodic intervals (often annually) to determine if the CMM still meets the manufacturer's specification.

**CMM calibration** – A task carried out on installation and then as necessary to determine the magnitude of all the twenty-one kinematic error sources. Often referred to as *error mapping* a CMM.

# ISO 10360-2: 2009 CMMs used for measuring linear dimensions

# 3

**IN THIS CHAPTER**

- Objectives of ISO 10360-2
- An overview of ISO 10360
- What's new in ISO 10360
- CMM test uncertainty
- Limitations of ISO 10360

The main tests of a CMM are detailed in part two of the series of ISO standards. This chapter aims to give the reader an overview of ISO 10360-2.

## Objectives of ISO 10360-2

The tests in this part of ISO 10360 have three technical objectives as listed in the standard:

- to test the error of indication of a calibrated test length using a probing system without any ram axis stylus tip offset;
- to test the error of indication of a calibrated test length using a probing system with a specified ram axis stylus tip offset; and
- to test the repeatability of measuring a calibrated test length.

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

Part 2 of ISO 10360 specifies performance requirements that can be assigned by the manufacturer or the user of a CMM. It also specifies the manner of execution of the acceptance and reverification tests to demonstrate the stated requirements, rules for proving conformance, and applications for which the acceptance and reverification tests can be used.

## An overview of ISO 10360

ISO 10360-2: 2009 describes the following tests:

- The acceptance test

  This test verifies that the performance of the CMM and that of the probing system is as stated by the manufacturer of the machine. It is the test carried out during the installation of the machine.

- The reverification test

  This test enables the end user to reverify the CMM and the probing system on a periodic basis, according to the user's requirements and the use of the machine.

- The interim check

  This check enables the end user to check the CMM and the probing system between regular reverification tests.

It used to be the case that one of the objectives of this specification standard was to enable the end user to carry out the tests in the most efficient way with the user free to specify the test locations and/or orientations anywhere within the working volume of the machine. This did not imply an omission or lack of care in formulating the standard, but rather ensured that the supplier of the measuring system could not readily optimise the performance along specific measuring lines. However, the standard now lists four required positions and three default positions with additional recommended lines for high aspect ratio CMMs.

The acceptance and verification tests of the CMM are essentially length-measuring tasks to ensure that the tests conform, as closely as possible, to frequently performed measurement procedures undertaken by the end user.

The probing error test is carried out at acceptance and reverification and is designed to assess probing errors that are associated with probing systems operating in the discrete point measuring mode. Because it is impossible to isolate probing errors from machine errors some additional system errors, that have both static and dynamic origins inherent in the CMM, for example, due to the CMM's servo system, will also be measured by this test.

It must be remembered that performance verification, *i.e.,* acceptance testing, reverification tests and interim checks do not guarantee traceability of measurement for all measurement tasks performed by the CMM. However, it is recognised that in an industrial environment these tests and checks are currently the closest approximation to traceability available to the user.

## What's new in ISO 10360

If you are familiar with previous versions of the specification standard you will note that the following changes have been introduced in the latest version.

- The principle of the assessment method is to use a calibrated test length, traceable to the metre, to establish whether the CMM is capable of measuring within the stated maximum permissible error of length measurement for a CMM with a specified ram axis stylus tip offset (both zero offset and 150 mm offset). Previously no offset was specified.

- The calibrated test length may now be a ball bar or laser interferometer system.

- The single stylus probing test that appeared in ISO 10360-2: 2001 does not appear in the current edition of ISO 10360-2. It has been moved to the new edition of ISO 10360-5 that will be replacing ISO 10360-5: 2000. ISO/PAS 12868 has been prepared to allow the single stylus probing test to be available until the publication of the new edition of ISO 10360-5. ISO 10360-5: 2010 has now been published and ISO/PAS 12868: 2009 cancelled.

- Many of the symbols used have changed and this is covered later in this guide.

## CMM test uncertainty

ISO/TS 23165: 2006 *Geometrical product specifications (GPS) – Guidelines for the evaluation of coordinate measuring machine (CMM) test uncertainty* provides guidance on how to calculate the uncertainty of measurement associated with the ISO 10360 tests. This guide will not attempt to repeat this guidance but reference will be made throughout this guide to the standard as appropriate.

## Limitations of ISO 10360

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, $P_{FTU}$, and length measurement errors, $E_L$, for the following reasons:

- choice of test locations;
- environmental conditions; and
- CMM repeatability.

This limitation 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.

# Basic terminology

# 4

**IN THIS CHAPTER**

- Material standard of size
- Error of indication
- Maximum permissible error of indication of a CMM for size measurement
- Ram axis stylus tip offset
- Symbols used in ISO 10360

Before describing the various tests and checks, the reader should be aware of some basic terminology. For the exact definition, reference should be made to ISO 10360-1. The user should be aware that some terms and definitions specified in ISO 10360-1 have been superseded by new definitions in ISO 10360-2.

## Material standard of size

ISO 10360 defines a material standard as a material measure reproducing a traceable value of a dimensional quantity of a feature and a material standard of size as a material standard reproducing a feature of size.

Early versions of ISO 10360 strongly recommended that the material standard should be either a step gauge (figure 1), end bar or a series of gauge blocks (figure 2) conforming to ISO 3650 *Geometrical Product Specifications (GPS) Length Standards Gauge blocks*. The material standard of size had to contain two or more nominally parallel planes, the distance between the planes being specified.

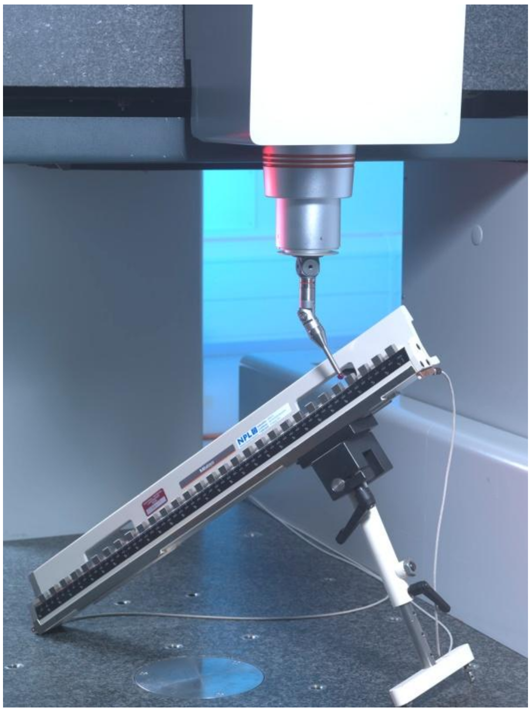


**Figure 1 A step gauge being used to verify a CMM**

In ISO 10360-2: 2009 the terminology now used is that of calibrated test length. Bi-directional measurements can make use of a gauge block, step gauge, ball bar or laser interferometer as long as the probing directions are opposite at either end of the calibrated test length. Uni-directional measurements may be made as long as they are supplemented by bi-directional measurements. Suitable calibrated test lengths can be obtained from step gauges, ball bars, laser interferometers with uni-direcrtional probing and laser interferometers without contact probing.

The material standard of size used for the tests must be calibrated. The uncertainty of calibration must be taken into consideration and the calibrations must be traceable to the relevant national standard.

**Figure 2 Gauge blocks and end bars**

**Coefficient of thermal expansion (CTE)**

How much the part material changes size for a given temperature change is known as the coefficient of linear thermal expansion. For a typical material such as steel this is expressed as $11.6 \times 10^{-6}$ ºC$^{-1}$. To correct a length to 20 ºC use the following equation:

$$L_{20} = L_{\mathrm{T}} + (20 - T) \cdot \alpha \cdot L_{\mathrm{T}}$$

where $L$ is length, $T$ is the temperature at which the length was measured and $\alpha$ is the coefficient of thermal expansion.

For example, a steel bar that is measured as 300.015 mm at a temperature of 23.4 ºC has a length of

$$300.015 + (20 - 23.4) \times 11.6 \times 10^{-6} \times 300.015 = 300.003 \text{ mm} .$$

Note that if the calibrated test length is not of a normal CTE material ($\alpha < 2 \times 10^{-6}$ ºC$^{-1}$) then the corresponding $E_{0,\,\mathrm{MPE}}$ and $E_{150,\,\mathrm{MPE}}$ values (see later) are designated with an asterisk (*) for example $E_{0,\,\mathrm{MPE}}^{*}$ and an explanatory note provided giving the material and CTE.

## Length measurement error of a CMM

The error of indication of a CMM for size measurement (length measurement error) is the error with which the size of the material standard can be determined by the CMM. The measurement being taken through the two opposite points on the two nominally parallel planes, normal to one of the planes. The probing head must approach the points from opposite directions.

The length measurement error of a CMM is expressed in micrometres (µm) and given by the symbol $E_L$.

## Maximum permissible error of indication of a CMM for size measurement

The term $E_{MPE, L}$ is the term most CMM users will be aware of. It is the term that specifies the length measuring accuracy of their CMM. $E_{MPE, L}$ is defined as the extreme value of the error of indication of a CMM for size measurement $E_L$, permitted by specifications, regulations, *etc*. for a CMM. The maximum permissible error of indication of a CMM for size measurement error, $E_{L, MPE}$, is stated in one of three forms:

a) $E_{L, MPE} = \pm$ minimum of $(A + L/K)$ and $B$ (see Figure 3);
b) $E_{L, MPE} = \pm\ (A + L/K)$ (see Figure 4); or
c) $E_{L, MPE} = \pm\ B$ (see Figure 5).

where

$A$ is a positive constant, expressed in micrometres and supplied by the manufacturer;
$K$ is a dimensionless positive constant supplied by the manufacturer;
$L$ is the measured size, in millimetres; and
$B$ is the maximum permissible error $E_{MPE, L}$, in micrometres, as stated by the manufacturer.

The expressions apply for any location and/or orientation of the material standard of size within the measuring volume of the CMM.

Measurements must be made utilising the three axes of the machine and the expressions apply for any position and orientation of the material standard within the working envelope of the CMM.

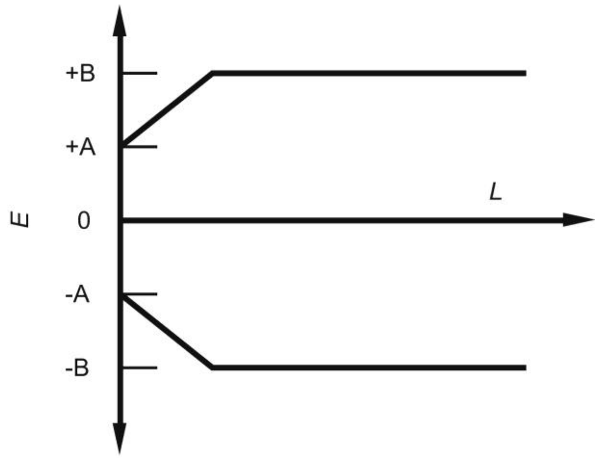



**Figure 3 CMM maximum permissible error of indication**

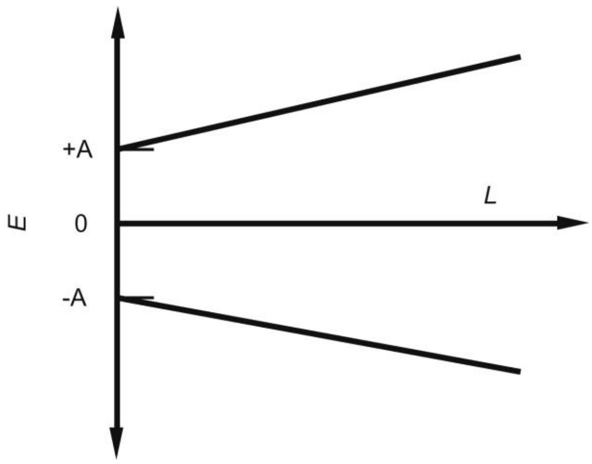



**Figure 4 CMM maximum permissible error of indication**

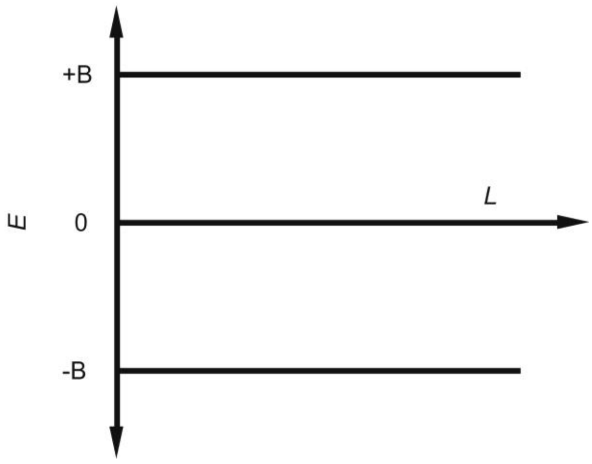



**Figure 5 CMM maximum permissible error of indication**

The maximum permissible error of length measurement $E_{L,\ MPE}$ is newly defined as the extreme value of the length measurement error, $E_L$, permitted by specifications. In part 2 of ISO 10360, $L$ = 0 mm and $L$ = 150 mm (default values) are specified.

It should be noted that a maximum permissible error (MPE) as opposed to a maximum permissible limit (MPL) specification is used when the test measurements determine errors, hence, testing an MPE specification requires the use of calibrated artefacts.

## Ram axis stylus tip offset

The latest version of the standard introduces the ram axis stylus tip offset. The ram axis stylus tip offset $L$ is the distance (orthogonal to the ram axis) between the stylus tip and a reference point. The manufacturer defines the reference point. If no manufacturer-defined reference point is known, the user chooses a reference point close to the probe system mount. The reference point is usually in or near the probe system.

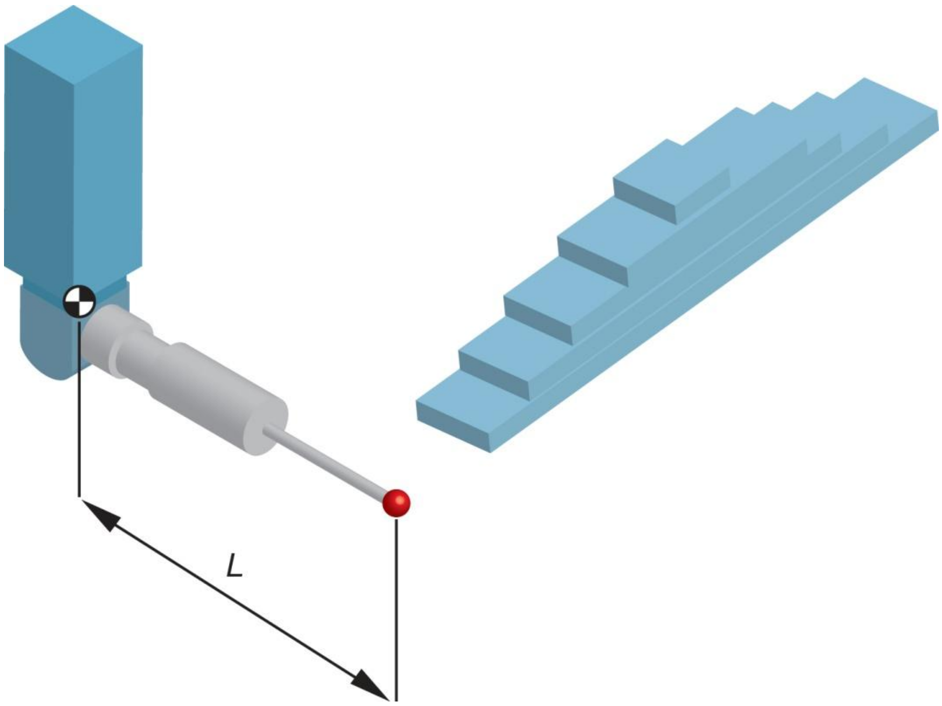



**Figure 6 An example of a ram axis stylus tip offset**

## Symbols used in ISO 10360

The symbols used in the standard are summarised below. Annex A of ISO 10360-5 gives a useful description of symbols and subscripts.

**Table 1 Symbols used in ISO 10360-2**

| Symbol | Meaning |
|---|---|
| $E_{\mathrm{L}}$ | Length measurement error |
| $R_0$ | Repeatability range of the length measurement error |
| $E_{\mathrm{L, MPE}}$ | Maximum permissible error of length measurement |
| $R_{\mathrm{0, MPL}}$ | Maximum permissible limit of the repeatability range |

To give an example, $E_{\mathrm{L}}$ could be written as $E_0$ or $E_{150.}$ The corresponding maximum permissible error would be $E_{\mathrm{0, MPE}}$ and $E_{\mathrm{150, MPE}}$.

Although the standard uses the above symbols it is accepted that they may not be suitable for product documentation, *etc.* and so the following alternatives are specified (see table 2). Table 3 shows the evolution of the symbols over the years.

**Table 2 Alternative symbols for product documentation**

| Symbol | Alternative |
|---|---|
| $E_{\mathrm{L}}$ | *EL* |
| $R_0$ | *R0* |
| $E_{\mathrm{L, MPE}}$ | MPE(*EL*) |
| $R_{\mathrm{0, MPL}}$ | MPL(*R0*) |

**Table 3 Symbols used historically**

| Meaning | 2009 | 2001 | 1995 |
|---|---|---|---|
| Length measurement error | $E_{\mathrm{L}}$ | $E$ | $\Delta L$ |
| Repeatability range of the length measurement error | $R_0$ | - | - |
| Maximum permissible error of length measurement | $E_{\mathrm{L,\ MPE}}$ | $\mathrm{MPE_E}$ | E |
| Maximum permissible limit of the repeatability range | $R_{\mathrm{0,\ MPL}}$ | - | - |
| Single stylus form error | $P_{\mathrm{FTU}}$ | P | $r_{max}$-$r_{min}$ |
| Maximum permissible single stylus form error | $P_{\mathrm{FTU,\ MPE}}$ | $\mathrm{MPE_P}$ | R |

Examples of the use of the symbols include

$E_0$ length measurement error with minimum offset (small as practicable).

$E_{\mathrm{0,\ MPE}}$ maximum permissible error of length measurement with minimal offset.

$E_{\mathrm{150,\ MPE}}$ maximum permissible error of length measurement with ram axis stylus tip offset of 150 mm.

# The acceptance test

# 5

**IN THIS CHAPTER**

- Preliminary actions
- Environmental conditions
- Operating Conditions
- Workpiece loading effects
- Checking the probing system prior to the ISO 10360-2 test
- Choice of measuring equipment
- Alternative artefacts
- Length measurement error with ram axis stylus tip offset of zero, $E_0$
- Calculation of results
- Length measurement error with ram axis stylus tip offset of 150 mm, $E_{150}$
- Repeatability range of the length measurement error
- Interpretation of the results

This chapter describes the acceptance test. The acceptance test would normally be performed on initial installation of the CMM or if the CMM has been overhauled or upgraded.

## Preliminary actions

Before and during the acceptance test the CMM must be operated in accordance with the procedure stated in the instruction manual for the CMM. This will include machine start up, probe qualification and probe configuration.

If the aim of the test is to verify that the machine meets its specification then the manufacturer's specified conditions, for example, length and type of stylus, probing speed, reference sphere *etc.* should be used. The environmental conditions recommended by the manufacturer should be adhered to.

It must be remembered that when carrying out the main length measurement verification of the CMM the probing system will have to be qualified using the manufacturer-supplied reference sphere (or other manufacturer-supplied artefact for probe qualifications). The results of the ISO 10360 test are only valid for measurements made with the same reference sphere. It is strongly recommended that the CMM be only used with the reference sphere supplied with the machine. For stylus systems with small stylus tips an alternative reference sphere may need to be used to qualify the stylus tip but it must be remembered that the results of the ISO 10360 test do not apply in the case where an alternative reference sphere is used.

It should also be noted that in the past some manufacturers have used the value of the reference sphere size in their software as a means of applying a crude software correction. In this case the size in the software for the reference sphere is not the same as the true size of the reference sphere. Care must be taken in these cases if the reference sphere is measured by an independent method, or a different reference sphere is used.

**Calibration of test and reference spheres**

NPL offers a service for the calibration of test and reference spheres. Further details can be found at www.npl.co.uk.

If the reference sphere is damaged it should be replaced with one of similar material and specification. The ISO 10360 test would then need to be repeated.

## Environmental conditions

The environment in which it operates will affect a CMM. Limits for permissible environmental conditions, such as temperature conditions, air humidity and vibration that influence the measurements are usually specified by the manufacturer. In the case of acceptance tests the environment specified by the manufacturer applies. However, in the case of reverification tests the user can specify the environment.

In both cases, the user is free to choose the environmental conditions under which the ISO 10360-2 testing will be performed within the specified limits.

The user is responsible for making sure that the environment surrounding the CMM, meets the manufacturer's specification.

## Operating Conditions

When performing the acceptance test the CMM should be operated using the procedures given in the manufacturer's operating manual.

Specific areas of the operating conditions that should be adhered to are, for example:

- machine start-up/warm-up cycles;
- stylus system configuration;
- cleaning procedures for stylus tip;
- probing system qualification;
- thermal stability of the probing system before calibration;
- weight of stylus system and/or probing system; and
- location, type, number of thermal sensors.

## Workpiece loading effects

The performance of any CMM will be affected by its loading. The length measurement specification of the CMM should apply up to the CMM's maximum specified loading. Clause 5.5 covers workpiece loading and states that testing of the length measurement error may be conducted under any workpiece load (from zero up to the rated maximum workpiece load), selected by the user subject to the following conditions:

- the physical volume of the load supplied for testing shall lie within the measuring volume of the CMM and the load shall be free-standing;
- the manufacturer may specify a limit on the maximum load per unit area (kg/m$^2$) on the CMM support (*i.e.* table) surface and/or on individual point loads (kg/cm$^2$); for point loads, the load at any specific contact point shall be no greater than twice the load of any other contact point; and
- unless otherwise specified by the manufacturer, the load shall be located approximately centrally and approximately symmetrically at the centre of the CMM table.

The user and the manufacturer should pay special consideration to the loading of the CMM table as any load may restrict access to measurement positions.

## Checking the probing system prior to the ISO 10360-2 test

Prior to carrying out the extensive testing described in this chapter it is recommended that a single-stylus probing system check is performed (see page 35). Annex B of ISO 10360-5 also suggests comparing the radius found with the calibrated size to give the single-stylus size error $P_{STU}$. The value obtained for $P_{STU}$ should be adequately small when compared to $E_{0,\,MPE}$ and $E_{L,\,MPE}$

## Choice of measuring equipment

The material standard of length to be used for the acceptance test is usually either a step gauge or a series of gauge blocks conforming to ISO 3650 *Geometrical Product Specifications (GPS) — Length standards - Gauge blocks*. If gauge blocks are used the user should choose five differing lengths, all meeting the criteria that the longest length of material standard should be at least 66 % of the longest space diagonal of the machine-operating envelope.

**Figure 7 An ISO 10360-2 test being carried out using gauge blocks**

For example, a CMM having an operating area of 2040 mm × 1300 mm and a maximum operating height of 570 mm has the longest space diagonal of 2485 mm.

In this case the longest length of the material standard, at a minimum of 66 % of the longest space diagonal, will be greater than or equal to 1640 mm.

The shortest length of material standard used in the acceptance test should be less than 30 mm.

ISO 10360-2: 1995 stated that if the manufacturer's material standard is used for the test, no additional uncertainty needs to be added to the value of *E*. If the user's material standard is used for the test and it has an uncertainty value, *F*, greater than 20 % of the value of *E*, then *E* should be redefined as the sum of *E* and *F*. However, since 2001 the rules stated in ISO 14253-1 have been applied (see Appendix C).

When the manufacturer or agent uses his or her own material standard of length to verify a CMM the end user should check that the calibration certificate for the standard is up to date and that the standard has been measured to an appropriate uncertainty. If the standard has been stored in an environment at a higher or lower temperature, *e.g.* the boot of a car, the user is advised to check that adequate time is allowed for the standard to reach thermal equilibrium with the measurement environment before being used.

Table 4 compares the advantages and disadvantages of the various standards of length.that may be used for verifying a CMM.

**Table 4 Comparison of various material standards of length**

| Standard | Features |
|---|---|
| Length Bars | Accuracy ≤ 0.5 µm/m<br>Only one length per bar<br>Easily damaged<br>Can become separated or lost |
| Gauge Blocks | Accuracy ≤ 0.5 µm/m<br>Only one length per bar<br>Easy to set up multiple arrangements<br>Requires supporting structure<br>More rigid than length bars<br>Easily damaged<br>Can become separated or lost |
| Step Gauges | Accuracy ≤ 1.0 µm/m<br>Multiplicity of length<br>Uni or bi-directional<br>Very rigid<br>Easily supported<br>More robust<br>Cannot become separated<br>Individual steps prone to move |

## Alternative artefacts

Information on artefacts that represent a calibrated test length can be found in Annex B of ISO 10360-2: 2009.

### *Laser interferometry with contact probing measured in a bi-directional manner*

A calibrated test length can be produced using a laser interferometer and a gauge block. The calibrated test length is then the sum of the calibrated length of the gauge block and the displacement recorded by a calibrated laser interferometer system. The use of laser interferometers is of particular advantage for larger CMMs. Note that for some CMMs tested with laser interferometry without contact probing, the CMM error map may not be applied to the results yielding an error of indication much larger than that obtained with contact probing.

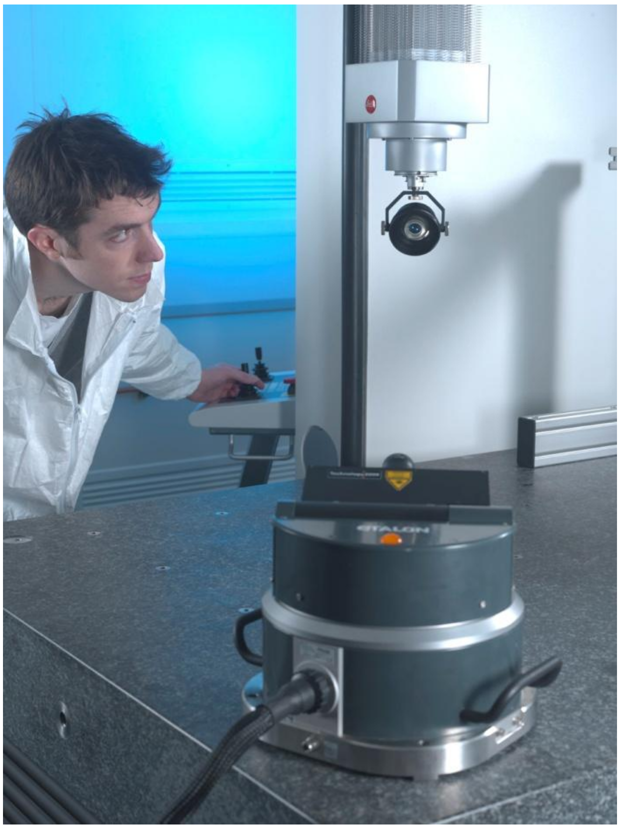


**Figure 8 A laser interferometer being used to verify a CMM**

When a laser interferometer is used to produce the test lengths the laser interferometer is considered to be a low CTE material, hence the need for the measurement of a normal CTE calibrated test length.

### *Ball bars or ball plates measured in a bi-directional manner*

A calibrated test length may be produced using a ball bar or ball plate where the length is equal to the calibrated sphere centre-to-centre length plus one half of the calibrated diameter of each sphere.

If uni-directional measurements are made then they must be supplemented by gauge block measurements.

## Length measurement error with ram axis stylus tip offset of zero, $E_0$

The first step is to qualify the probing system using the manufacturer's procedure ensuring that any particles of dust, rust or any finger marks are removed from the reference sphere and stylus tip. Next, the calibrated test length is measured. The measurement surfaces of the calibrated test length being used should be examined for signs of finger marks and dust and cleaned as necessary.

The user will need to take supplementary measurements for alignment purposes (for example probing the side face of a step gauge – see Annex C of ISO 10360-2). The alignment should be consistent with the procedures used for the calibration of the artefact. It is important that reference is made to the latest calibration certificate for the artefact is being used. As stated on page 14 the calibration of the test length should be traceable, preferably through the use of a national or accredited measurement laboratory.

**Calibration of step gauges and gauge blocks**

NPL offers a service for the calibration of length bars, gauge blocks and step gauges. Further details can be found at www.npl.co.uk.

To carry out the acceptance test the calibrated test length should be measured in any seven different combinations of position and orientation, three of the positions being chosen by the user. The remaining four positions consist of the space diagonals. For each of the seven orientations five test lengths are measured three times. The manufacturer may have pre-written software in place to carry out the test at pre-defined positions. The user should give the manufacturer plenty of notice as to the location of the three non-mandatory positions and orientation he or she would prefer in case reprogramming of the CMM verification software is necessary.

The length standard should be supported at the appropriate support points (usually the 'Airy points'). The 'Airy points', ensure that the surfaces towards the ends of the bar are parallel with its axis. For a horizontally supported bar the Airy points are separated by $0.577l$ (where $l$ is the length of the material standard). Manufacturers of step gauges often indicate the support points for both horizontal and 45° orientations, to give minimum deflection. For further information see NPL Measurement Good Practice Guide Number 80.

For a minimal offset the choice of location of the material standard in the CMM measuring volume will include some of the following positions. Positions 1 to 4 are mandatory. If the user specifies no other positions, positions 5 to 7 are the default positions.

- The four cross diagonals (required).
- The three in-plane diagonals (diagonals of *XY*, *YZ* and *XZ* planes at the mid position of the third axis).
- Measuring lines nominally parallel to an axis (the manufacturer may specify a separate maximum permissible error for these directions).

**Table 5 Orientation on the measuring volume**

| Position Number | Orientation in the measuring volume |
|---|---|
| 1 | Along the diagonal in space from point (1, 0, 0) to (0, 1, 1) |
| 2 | Along the diagonal in space from point (1, 1, 0) to (0, 0, 1) |
| 3 | Along the diagonal in space from point (0, 1, 0) to (1, 0, 1) |
| 4 | Along the diagonal in space from point (0, 0, 0) to (1, 1, 1) |
| 5 | Parallel to the machine scales from point (0,½, ½) to (1, ½, ½) |
| 6 | Parallel to the machine scales from point (½,0, ½) to (½, 1, ½) |
| 7 | Parallel to the machine scales from point (½,½, 0) to (½, ½, 1) |
| Note: For specifications in this table, opposite corners of the measuring volume are assumed to be (0, 0, 0) and (1, 1, 1) in co-ordinates (*X*, *Y*, *Z*) | |

Figure 9 shows some example measuring lines.

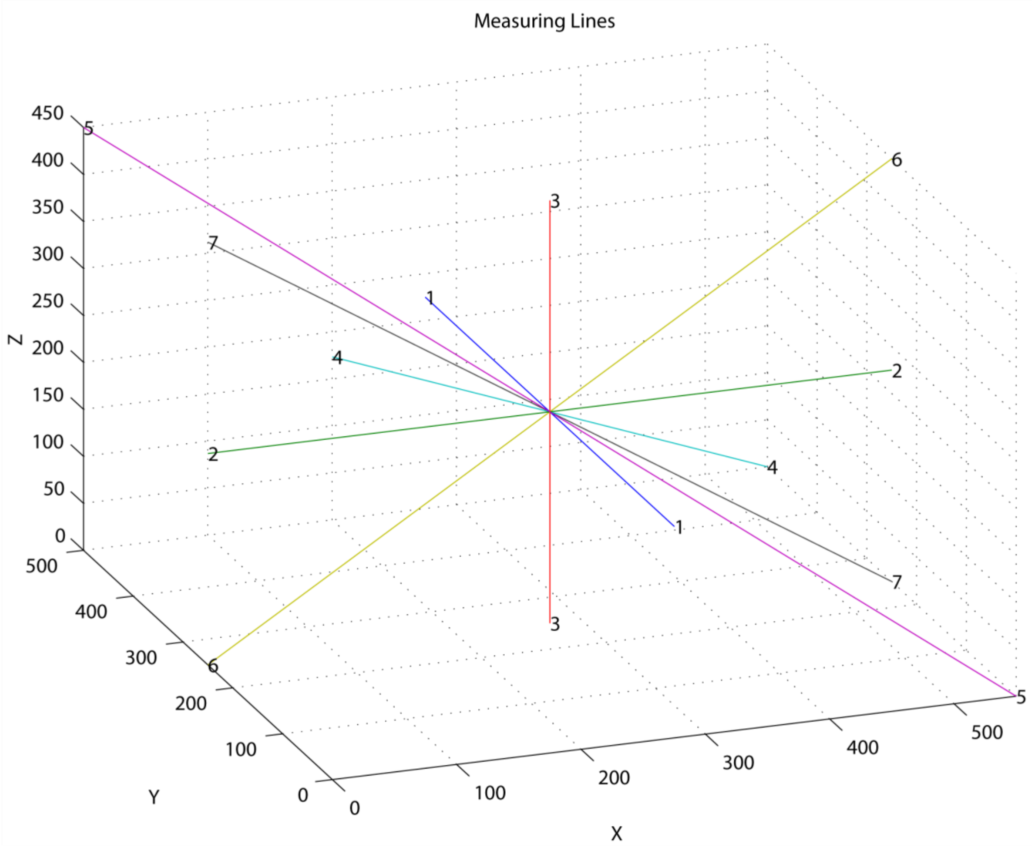



**Figure 9 Example measuring lines**

If the user carries out an ISO 10360 test but relies on the manufacturer for service the choice of measurement lines may serve as a check on whether adjustments made, for instance to the machines squareness, were justified.

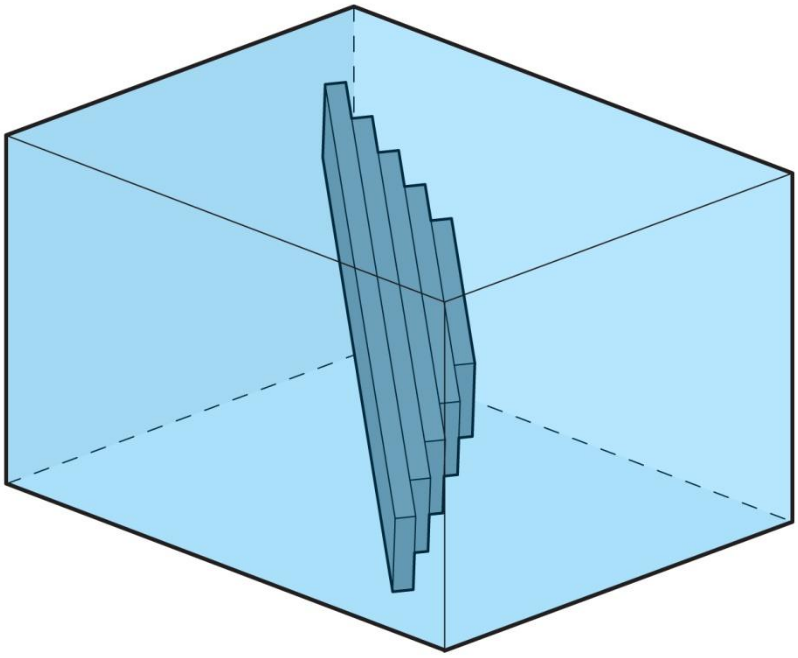


**Figure 10 Example position and orientation of gauge blocks**

For each of the seven configurations the user should take and record the measurements of the five test lengths, each test length being measured three times. For gauge blocks and length bars each material standard should be probed once at each end. For a step gauge make sure that a length consists of two probings in opposite direction. The fifteen measurements on the five test lengths in one position and orientation are regarded as one configuration.

Note that each of the three repeated measurements is to be arranged in the following manner: if one end of the calibrated test length is labelled “A” and the other end “B”, then the measurement sequence is either $A_1$ $B_1$, $A_2$ $B_2$, $A_3$ $B_3$ or $A_1$ $B_1$, $B_2$ $A_2$, $A_3$ $B_3$.

After completion of the test in the seven configurations a total of 105 measurements will have been made.

## Calculation of results

For each of the 105 measurements the error of length measurement, $E_L$ is calculated. This value is the absolute value of the difference between the indicated value of the relevant test length and the true value of the material standard. Particular attention should be made to Appendix D of ISO 10360-2 when using artefacts of low CTE.

The indicated value may be corrected to account for systematic errors if the CMM has accessory devices or software for this purpose. If the environmental conditions in operation for the test are those recommended by the manufacturer then no manual correction to the indicated values may be made manually by the user.

The true value of the material standard of length is taken as the calibrated length between the measuring faces. This value should be temperature corrected only if this facility is normally available in the software of the CMM. Table 6 gives an example of the calculations required.

From table 6 it can be seen that four of the thirty-five test lengths have values of the error of length measurement greater than $E_{0,\ MPE}$. These four values will have to be measured again ten times each at the relevant configuration (see the section on Data rejection and repeated measurements).

The output from another measuring machine verification is shown in figure 11. For each measuring line three determinations of the errors have been made. The dotted lines show the upper and lower error bounds ($E_{0,\ MPE}$).

**Table 6 Example of acceptance test results and computation (units: mm)**

Manufacturer's constant A **4**
Manufacturer's constant K **200**

| Configuration test number | Material standard of length True value | Indicated values | | | Error of length E0 | | | Error of indication $E_{0, MPE}$ |
|---|---|---|---|---|---|---|---|---|
| | | number 1 | number 2 | number 3 | number 1 | number 2 | number 3 | |
| 1 | 1699.999 | 1700.006 | 1700.007 | 1700.003 | 0.007 | 0.008 | 0.004 | 0.0125 |
| | 500.001 | 500.005 | 500.003 | 500.005 | 0.004 | 0.002 | 0.004 | 0.0065 |
| | 249.999 | 250.003 | 250.000 | 250.002 | 0.004 | 0.001 | 0.003 | 0.0053 |
| | 100.000 | 99.999 | 99.997 | 99.997 | 0.001 | 0.003 | 0.003 | 0.0045 |
| | 25.001 | 24.999 | 24.998 | 25.000 | 0.002 | 0.003 | 0.001 | 0.0041 |
| 2 | 1699.999 | 1699.998 | 1699.995 | 1700.001 | 0.001 | 0.004 | 0.002 | 0.0125 |
| | 500.001 | 500.000 | 499.998 | 499.999 | 0.001 | 0.003 | 0.002 | 0.0065 |
| | 249.999 | 250.000 | 249.998 | 249.999 | 0.001 | 0.001 | 0.000 | 0.0053 |
| | 100.000 | 99.999 | 99.997 | 100.001 | 0.001 | 0.003 | 0.001 | 0.0045 |
| | 25.001 | 25.000 | 25.002 | 25.001 | 0.001 | 0.001 | 0.000 | 0.0041 |
| 3 | 1699.999 | 1700.001 | 1700.000 | 1699.999 | 0.002 | 0.001 | 0.000 | 0.0125 |
| | 500.001 | 500.005 | 500.003 | 500.000 | 0.004 | 0.002 | 0.001 | 0.0065 |
| | 249.999 | 250.001 | 250.004 | 250.000 | 0.002 | 0.005 | 0.001 | 0.0053 |
| | 100.000 | 100.000 | 99.999 | 99.998 | 0.000 | 0.001 | 0.002 | 0.0045 |
| | 25.001 | 24.999 | 24.997 | 24.997 | 0.002 | 0.004 | 0.004 | 0.0041 |
| 4 | 1699.999 | 1700.001 | 1699.999 | 1699.997 | 0.002 | 0.000 | 0.002 | 0.0125 |
| | 500.001 | 499.996 | 499.999 | 500.000 | 0.005 | 0.002 | 0.001 | 0.0065 |
| | 249.999 | 250.003 | 250.000 | 250.001 | 0.004 | 0.001 | 0.002 | 0.0053 |
| | 100.000 | 100.005 | 100.004 | 100.002 | 0.005 | 0.004 | 0.002 | 0.0045 |
| | 25.001 | 25.003 | 24.999 | 24.998 | 0.002 | 0.002 | 0.003 | 0.0041 |
| 5 | 1699.999 | 1699.997 | 1699.994 | 1699.999 | 0.002 | 0.005 | 0.000 | 0.0125 |
| | 500.001 | 500.001 | 499.999 | 499.995 | 0.000 | 0.002 | 0.006 | 0.0065 |
| | 249.999 | 250.000 | 249.998 | 249.999 | 0.001 | 0.001 | 0.000 | 0.0053 |
| | 100.000 | 99.998 | 99.995 | 100.000 | 0.002 | 0.005 | 0.000 | 0.0045 |
| | 25.001 | 24.996 | 24.998 | 24.997 | 0.005 | 0.003 | 0.004 | 0.0041 |
| 6 | 1699.999 | 1699.999 | 1699.997 | 1700.000 | 0.000 | 0.002 | 0.001 | 0.0125 |
| | 500.001 | 499.997 | 500.000 | 500.002 | 0.004 | 0.001 | 0.001 | 0.0065 |
| | 249.999 | 250.003 | 250.004 | 250.001 | 0.004 | 0.005 | 0.002 | 0.0053 |
| | 100.000 | 100.000 | 99.996 | 99.998 | 0.000 | 0.004 | 0.002 | 0.0045 |
| | 25.001 | 25.001 | 25.004 | 25.000 | 0.000 | 0.003 | 0.001 | 0.0041 |
| 7 | 1699.999 | 1700.006 | 1699.998 | 1700.004 | 0.007 | 0.001 | 0.005 | 0.0125 |
| | 500.001 | 500.000 | 500.005 | 500.004 | 0.001 | 0.004 | 0.003 | 0.0065 |
| | 249.999 | 249.999 | 249.995 | 249.997 | 0.000 | 0.004 | 0.002 | 0.0053 |
| | 100.000 | 100.007 | 100.003 | 100.001 | 0.007 | 0.003 | 0.001 | 0.0045 |
| | 25.001 | 25.004 | 25.001 | 25.001 | 0.003 | 0.000 | 0.000 | 0.0041 |

(grey shading) Indicates error of length measurement greater than $E_{0, MPE}$

$$E = A + L/K$$

*for 1700 mm* $E = 4 + 1700/200 = 12.5\ \mu m$

*for 500 mm* $E = 4 + 500/200 = 6.5\ \mu m$

*for 250 mm* $E = 4 + 250/200 = 5.25\ \mu m$

*for 100 mm* $E = 4 + 100/200 = 4.5\ \mu m$

*for 25 mm* $E = 4 + 25/200 = 4.125\ \mu m$

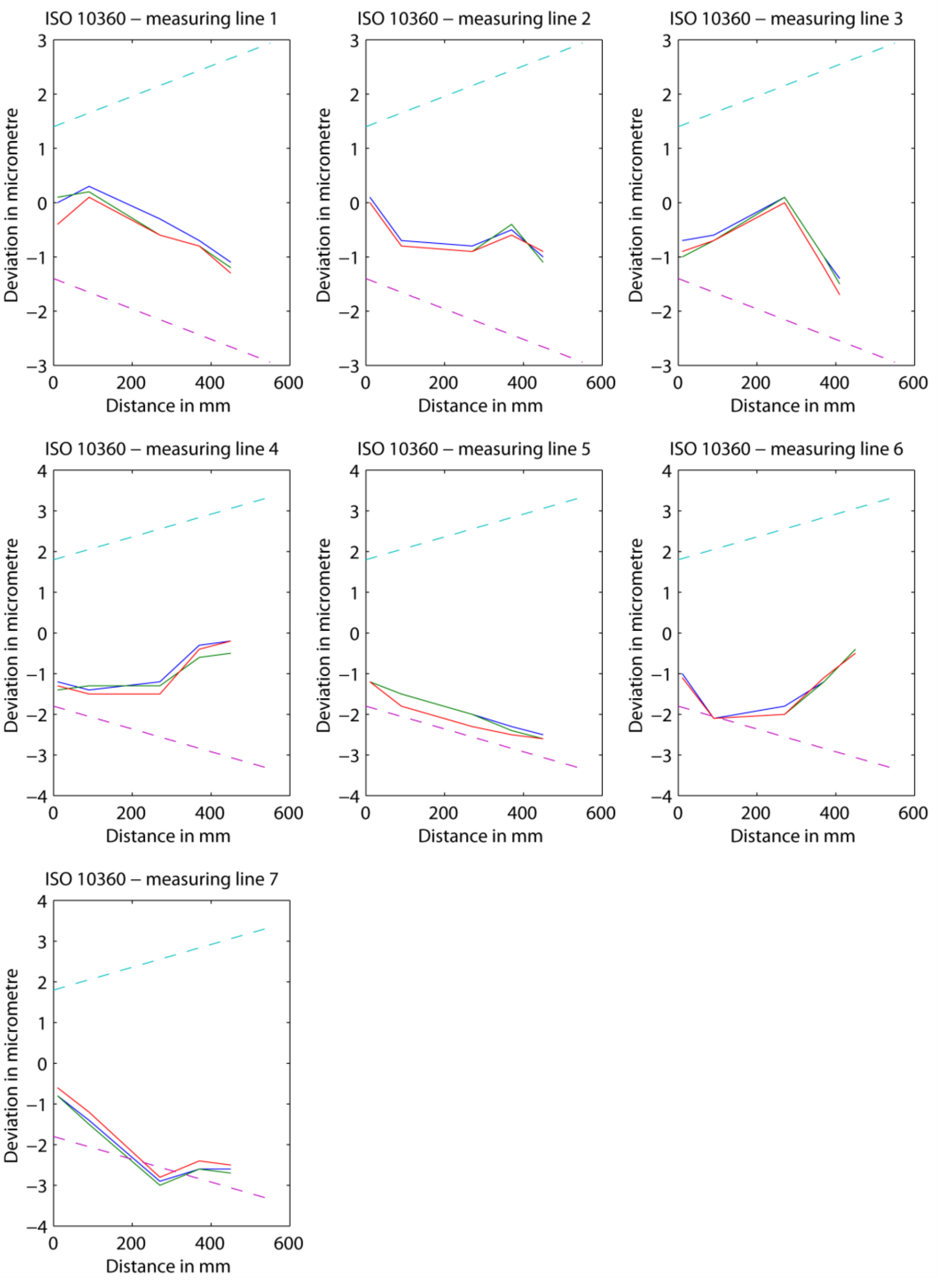



**Figure 11 Graphical representation of ISO 10360 test**

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

This test is carried out under similar conditions as those for the test with no offset.

The default value for the ram axis stylus tip offset is 150 mm (± 15 mm), *i.e.* $E_{150}$.

The direction of the ram axis stylus tip offset should be oriented perpendicular to the measurement line defined by the calibrated test length and pointing along a CMM axis direction. For each measurement, the user may specify the direction of the ram axis stylus tip offset to be pointing either in the positive or in the negative axis direction, *i.e.* in either the +X or –X direction for positions 1A or 1B, and in either the +*Y* or –*Y* direction for positions 2A or 2B. Hence, of the eight possible combinations of test length positions and probe orientations, the user may choose any two for testing.

**Table 7 Orientation in the measuring volume**

| Position Number | Orientation in the measuring volume |
|---|---|
| 1A | Along the *YZ* plane diagonal from point (½,0, 0) to (½, 1, 1) |
| 1B | Along the *YZ* plane diagonal from point (½,0, 1) to (½, 1, 0) |
| 2A | Along the *XZ* plane diagonal from point (0,½, 0) to (1, ½, 1) |
| 2B | Along the *XZ* plane diagonal from point (0,½, 1) to (1, ½, 0) |
| Note For specifications in this table, opposite corners of the measuring volume are assumed to be (0, 0, 0) and (1, 1, 1) in co-ordinates (*X*, *Y*, *Z*) | |

The position of the stylus tip in the direction of the ram axis should be significantly different from that used for the $E_0$ test.

## Repeatability range of the length measurement error

There is now a requirement to determine the repeatability range of the three repeated length measurements $R_0$.

The values of $R_0$ should be plotted to allow comparison with $R_{0,\ \mathrm{MPL}}$.

## Interpretation of the results

### *Acceptance test*

The 105 length measurement error values ($E_0$) are compared with the manufacturers stated value of $E_{0,\ \mathrm{MPE}}$. If none of the error of length values is greater than $E_{0,\ MPE}$ then the performance of the CMM is verified. Account should be made of the measurement uncertainty according to ISO 14253-1 and ISO/TS 23165. The repeatability range of the length measurement error $R_0$ should also be within the maximum permissible limit of the repeatability range, $R_{0,\ MPL}$ as specified by the manufacturer. Finally the length measurement error measured with a ram axis stylus tip offset of 150 mm ($E_{150}$) should be within the manufacturers specification for the maximum permissible error of length measurement $E_{150,\ MPE.}$

### *Data rejection and repeated measurements*

A maximum of five of the thirty-five test length measurements may have one (and no more that one) of the three values of the error of length measurement greater than $E_{0,\ MPE}$. If this is so then it is necessary for each out of tolerance test length to be measured three times at the relevant configuration. If all the error of length values recorded from the repeat measurements are within $E_{0,\ MPE}$, then the performance of the CMM is verified.

If a calibrated test length is re-measured, then the range of the three repeated measurements shall be used to determine $R_0$ at that position, and the three original measurements shall be discarded.

For the length measurement error with ram axis stylus tip offset of 150 mm, $E_{150}$ a maximum of two of the ten sets of three repeated measurements may have one of the three values of the length measurement error outside the conformance zone. Each such measurement that is out of the conformance zone, taking in to account ISO 14253-1 rules, shall be re-measured three times at the relevant position. If all the values of the errors of indication of a calibrated test length with ram axis stylus tip offset of 150 mm from the three repeated measurements are within the conformance zone (again taking in to account ISO 14253-1 rules), then the performance of the CMM is verified at that position.

### *Reverification test*

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

# Acceptance test of the CMM probing system

6

**IN THIS CHAPTER**

- Acceptance test of the CMM probing system
- Probing error
- Acceptance test procedure
- Calculation of results
- Interpretation of results

The single stylus probing test that appeared in ISO 10360-2: 2001 does not appear in the current edition of ISO 10360-2. It has been moved to the new edition of ISO 10360-5 that will be replacing ISO 10360-5: 2000. ISO/PAS 12868 was prepared to allow the single stylus probing test to be available until the publication of the new edition of ISO 10360-5. ISO/PAS 12868 has been withdrawn with the publication of ISO10360-5: 2010.

## Acceptance test of the CMM probing system

This test of the CMM probing system is used to establish whether the CMM is capable of measuring within the manufacturer's stated value of $P_{\mathrm{FTU,\ MPE}}$ by determining the range of values of the radial distance $r$ when measuring a reference sphere. **It is advisable to carry out this test before an acceptance or reverification test**.

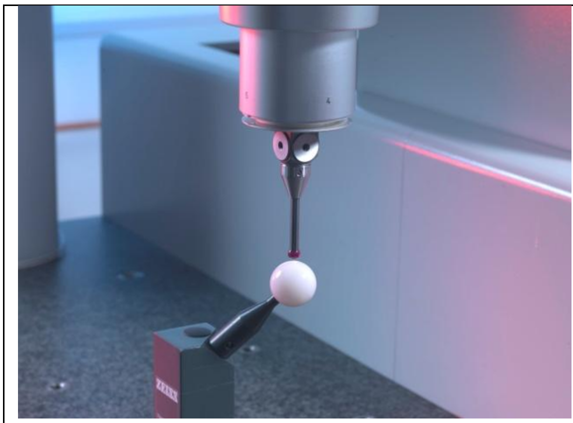
## Probing error $P_{\mathrm{FTU,\ MPE}}$

$P_{\mathrm{FTU,\ MPE}}$ is the error within which the range of radii of a material standard can be determined with a CMM, the measurements being taken using a sphere as the artefact.

**Explanation of the nomenclature $P_{\mathrm{FTU}}$**

P: associated with the probing system
F: apparent Form error
T: contact probing (that is to say Tactile)
U: single (that is to say Unique)

**The sphere supplied by the manufacturer for probe qualifying purposes (reference sphere) should not be used for the probing error test.**

<table>
<tr><td><br>**Figure 12 Reference sphere should not be used**</td><td><br><br>**Figure 13 Use a suitable test sphere**</td></tr>
<tr><td>Wrong</td><td>Correct</td></tr>
</table>

The probing error is a positive constant, the value of which is supplied by the CMM manufacturer. It applies to any location of the test sphere within the working envelope and for any probing direction.

The test sphere should be between 10 mm and 50 mm diameter. The form of the test sphere shall be calibrated, since the form deviation influences the test result, and shall be taken into account when proving conformance or non-conformance with the specification using ISO 14253 decision rules. The test sphere should be mounted rigidly to overcome errors due to bending of the mounting stem. Spheres up to 30 mm in diameter are commonly used. A small sphere is advantageous as there is less likelihood of machine errors contributing to the probing error. The standard recommends that the form error of the test sphere should not exceed 20 % of $P_{\mathrm{FTM,\ MPE}}$ or $P_{\mathrm{FTN,\ MPE}}$ as relevant.

## Acceptance test procedure

The user can choose the configuration of the stylus components of the probe but this must be within the limits specified by the manufacturer. The single stylus length should be chosen from one of the lengths specified in the standards, *i.e.*, 20 mm, 30 mm, 50 mm, 100 mm. A stylus length variation of 6 mm or 10 % of the nominal length, whichever is the greater, may be used.

**ISO 10360-2: 1995 and ISO 10360-2: 2001 recommended that the orientation of the stylus should not be parallel to any CMM axis. However, ISO 10360-5 now states that the stylus orientation shall be parallel to the ram axis, unless otherwise specified.**

It is necessary to qualify the probing system according to the manufacturer's procedures making sure that any particles of dust, rust or any finger marks are removed from the reference sphere and stylus tip. If rust is often noticed on the reference sphere it may be worth permanently changing it for one of an alternative material.

The next step is to mounts the test sphere on the machine removing all dust particles and finger marks. It is a requirement of the standards that one location of the test sphere shall be chosen by the user anywhere in the measuring volume.

Twenty-five points are measured and recorded. It is a requirement that the points are approximately evenly distributed over at least a hemisphere of the test sphere. Their position is at the discretion of the user and, if not specified, the following probing pattern is recommended (see figure 14):

- one point on the pole (defined by the direction of the stylus shaft) of the test sphere;
- four points (equally spaced) 22.5° below the pole;
- eight points (equally spaced) 45° below the pole and rotated 22.5° relative to the previous group;
- four points (equally spaced) 67.5° below the pole and rotated 22.5° relative to the previous group; and
- eight points (equally spaced) 90° below the pole (*i.e.*, on the equator) and rotated 22.5° relative to the previous group.

For direct computer control (DCC) machines it is suggested that the test be performed with a computer numeric control (CNC) program.

For manually operated machines the above test can be difficult to perform. It is suggested that the operator calculate the nominal positions of twenty-five points on the hemi-sphere prior to the test and then aims to probe these points.

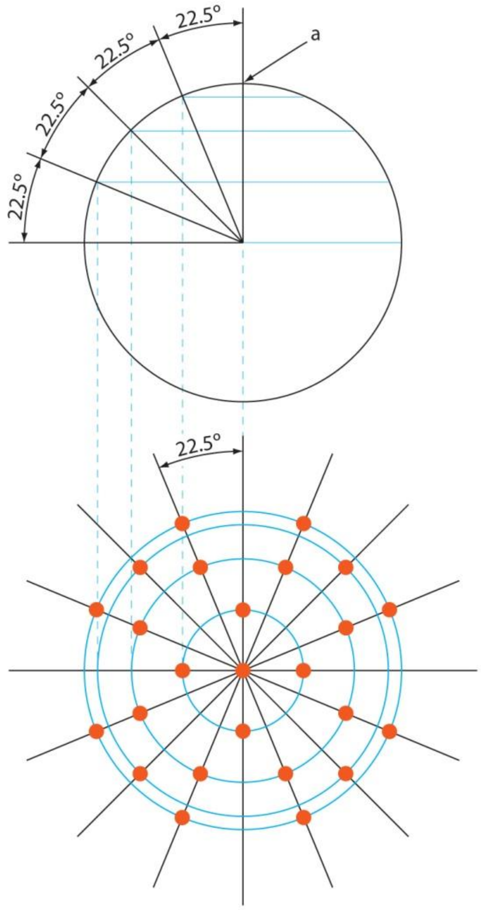



**Figure 14 Recommended probing pattern (a indicates the pole)**

# Calculation of results

From the data the Gaussian (least squares) sphere (substitution element) is computed using all twenty-five points. For each of the twenty-five measurements the radial distance *r* is calculated. This distance is the distance between the calculated centre of the sphere and the probed point.

The steps might be:

1. probe the twenty-five points (element point) on the sphere;
2. recall the points to form a sphere;
3. zero the centre of the sphere;
4. recall the twenty-five points into the new co-ordinate system; and
5. calculate the polar distance of the points from the origin.

An alternative method would be:

1. probe a suitable number of points using the sphere feature;
2. zero the centre of the sphere;
3. probe twenty-five points on the sphere surface; and
4. calculate the polar distance (radius) of the points from the origin (see table 8).

**Table 8 Typical sphere test data (values in millimetres)**

| Point | X | Y | Z | Radial distance |
|---|---|---|---|---|
| 1 | 0.00154 | -0.00566 | 17.49219 | **14.99204** |
| 2 | 6.70387 | -0.00891 | 16.15692 | 14.99236 |
| 3 | 0.00455 | 6.69511 | 16.16072 | 14.99251 |
| 4 | -6.69846 | -0.00374 | 16.15924 | 14.99243 |
| 5 | 0.00596 | -6.70615 | 16.15614 | 14.99251 |
| 6 | 11.43117 | 4.72465 | 12.36909 | 14.99237 |
| 7 | 4.73375 | 11.42388 | 12.37212 | 14.99221 |
| 8 | -4.73015 | 11.42566 | 12.37196 | 14.99229 |
| 9 | -11.42907 | 4.73257 | 12.36782 | 14.99224 |
| 10 | -11.42715 | -4.74161 | 12.36620 | 14.99229 |
| 11 | -4.72610 | -11.43490 | 12.36527 | 14.99250 |
| 12 | 4.73293 | -11.43309 | 12.36426 | 14.99245 |
| 13 | 11.42905 | -4.73703 | 12.36618 | 14.99227 |
| 14 | 11.43514 | 11.42128 | 6.69123 | 14.99215 |
| 15 | -11.43024 | 11.42667 | 6.69062 | 14.99223 |
| 16 | -11.42537 | -11.43558 | 6.68438 | 14.99249 |
| 17 | 11.42750 | -11.43036 | 6.68982 | 14.99254 |
| 18 | 16.16229 | 6.69052 | -0.00024 | 14.99221 |
| 19 | 6.70185 | 16.15752 | -0.00234 | 14.99214 |
| 20 | -6.69619 | 16.16008 | -0.00574 | 14.99234 |
| 21 | -16.16095 | 6.69370 | -0.00892 | 14.99218 |
| 22 | -16.15590 | -6.70562 | -0.00912 | 14.99209 |
| 23 | -6.68965 | -16.16316 | -0.00509 | **14.99268** |
| 24 | 6.69574 | -16.16043 | -0.00373 | 14.99249 |
| 25 | 16.15706 | -6.70349 | -0.00010 | 14.99234 |

For the above example the range of radial distances is 0.000 64 mm.

The radial distance (polar distance) is calculated from $\sqrt{x^2 + y^2 + z^2}$. In table 8 the maximum and minimum values are highlighted. The calibrated diameter of the sphere was 29.985 00 mm and the departure from roundness 0.000 052 mm. The measured diameter from the CMM was 29.984 6 mm (see page 23 Checking the probing system prior to the ISO 10360-2 test).

## Interpretation of results

If the range $r_{max}$ - $r_{min}$ of the twenty-five radial distances ($P_{FTU}$) is no greater than the manufacturer's stated value of $P_{FTU,\ MPE}$ when taking into account the measurement uncertainty, then the performance of the probing system is verified.

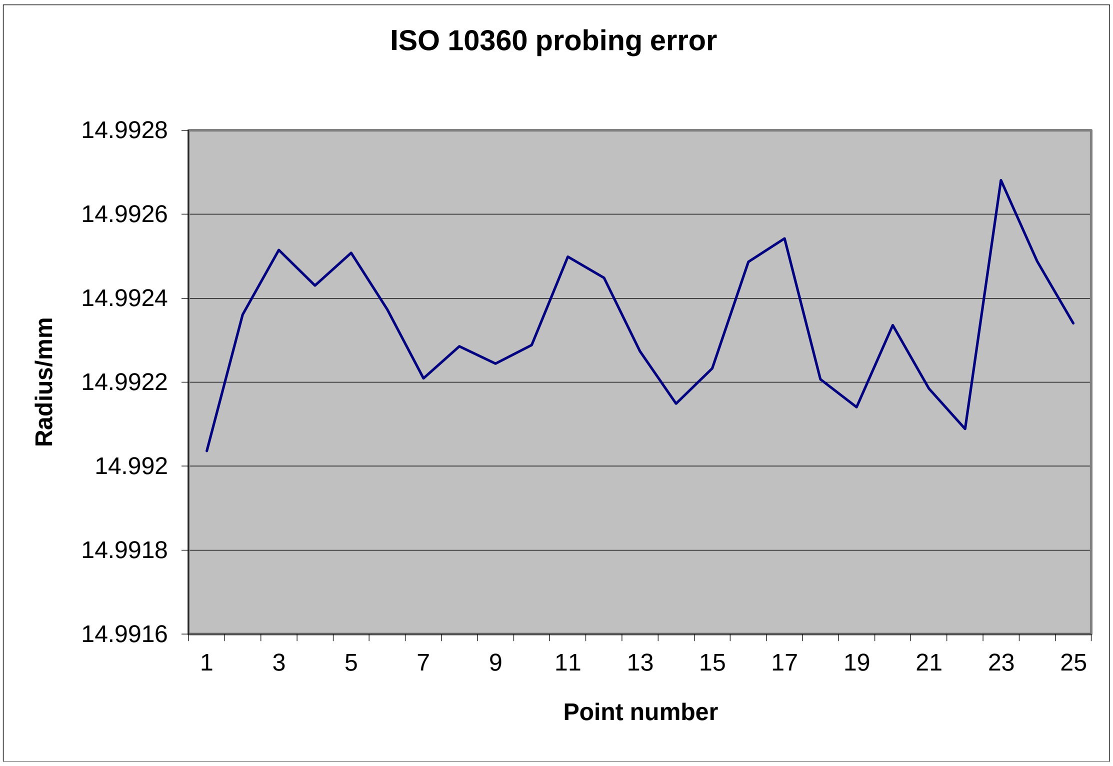
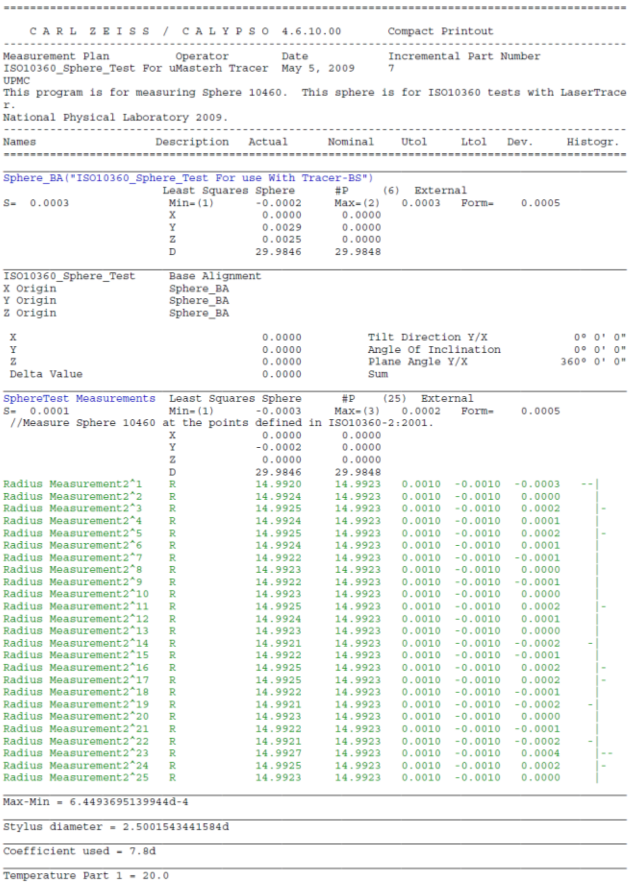



**Figure 15 Example results from a probe test**



```
==========================================================================================
    C A R L  Z E I S S  /  C A L Y P S O  4.6.10.00        Compact Printout
------------------------------------------------------------------------------------------
Measurement Plan          Operator        Date            Incremental Part Number
ISO10360_Sphere_Test For uMasterh Tracer  May 5, 2009     7
UPMC
This program is for measuring Sphere 10460.  This sphere is for ISO10360 tests with LaserTrace
r.
National Physical Laboratory 2009.
------------------------------------------------------------------------------------------
Names                  Description  Actual      Nominal   Utol     Ltol    Dev.     Histogr.
==========================================================================================
__________________________________________________________________________________________
Sphere_BA("ISO10360_Sphere_Test For use With Tracer-BS")
                        Least Squares Sphere      #P     (6)  External
S=  0.0003               Min=(1)      -0.0002     Max=(2)   0.0003   Form=    0.0005
                         X             0.0000      0.0000
                         Y             0.0029      0.0000
                         Z             0.0025      0.0000
                         D            29.9846     29.9848
__________________________________________________________________________________________
ISO10360_Sphere_Test     Base Alignment
X Origin                 Sphere_BA
Y Origin                 Sphere_BA
Z Origin                 Sphere_BA

 X                                     0.0000          Tilt Direction Y/X              0° 0' 0"
 Y                                     0.0000          Angle Of Inclination            0° 0' 0"
 Z                                     0.0000          Plane Angle Y/X               360° 0' 0"
 Delta Value                           0.0000          Sum
__________________________________________________________________________________________
SphereTest Measurements  Least Squares Sphere      #P    (25)  External
S=  0.0001               Min=(1)      -0.0003     Max=(3)   0.0002   Form=    0.0005
 //Measure Sphere 10460 at the points defined in ISO10360-2:2001.
                         X             0.0000      0.0000
                         Y            -0.0002      0.0000
                         Z             0.0000      0.0000
                         D            29.9846     29.9848
Radius Measurement2^1    R            14.9920     14.9923   0.0010  -0.0010  -0.0003   --|
Radius Measurement2^2    R            14.9924     14.9923   0.0010  -0.0010   0.0000     |
Radius Measurement2^3    R            14.9925     14.9923   0.0010  -0.0010   0.0002     |-
Radius Measurement2^4    R            14.9924     14.9923   0.0010  -0.0010   0.0001     |
Radius Measurement2^5    R            14.9925     14.9923   0.0010  -0.0010   0.0002     |-
Radius Measurement2^6    R            14.9924     14.9923   0.0010  -0.0010   0.0001     |
Radius Measurement2^7    R            14.9922     14.9923   0.0010  -0.0010  -0.0001     |
Radius Measurement2^8    R            14.9923     14.9923   0.0010  -0.0010   0.0000     |
Radius Measurement2^9    R            14.9922     14.9923   0.0010  -0.0010  -0.0001     |
Radius Measurement2^10   R            14.9923     14.9923   0.0010  -0.0010   0.0000     |
Radius Measurement2^11   R            14.9925     14.9923   0.0010  -0.0010   0.0002     |-
Radius Measurement2^12   R            14.9924     14.9923   0.0010  -0.0010   0.0001     |
Radius Measurement2^13   R            14.9923     14.9923   0.0010  -0.0010   0.0000     |
Radius Measurement2^14   R            14.9921     14.9923   0.0010  -0.0010  -0.0002    -|
Radius Measurement2^15   R            14.9922     14.9923   0.0010  -0.0010  -0.0001     |
Radius Measurement2^16   R            14.9925     14.9923   0.0010  -0.0010   0.0002     |-
Radius Measurement2^17   R            14.9925     14.9923   0.0010  -0.0010   0.0002     |-
Radius Measurement2^18   R            14.9922     14.9923   0.0010  -0.0010  -0.0001     |
Radius Measurement2^19   R            14.9921     14.9923   0.0010  -0.0010  -0.0002    -|
Radius Measurement2^20   R            14.9923     14.9923   0.0010  -0.0010   0.0000     |
Radius Measurement2^21   R            14.9922     14.9923   0.0010  -0.0010  -0.0001     |
Radius Measurement2^22   R            14.9921     14.9923   0.0010  -0.0010  -0.0002    -|
Radius Measurement2^23   R            14.9927     14.9923   0.0010  -0.0010   0.0004     |--
Radius Measurement2^24   R            14.9925     14.9923   0.0010  -0.0010   0.0002     |-
Radius Measurement2^25   R            14.9923     14.9923   0.0010  -0.0010   0.0000     |
__________________________________________________________________________________________
Max-Min = 6.44936951399944d-4
__________________________________________________________________________________________
Stylus diameter = 2.5001543441584d
__________________________________________________________________________________________
Coefficient used = 7.8d
__________________________________________________________________________________________
Temperature Part 1 = 20.0
__________________________________________________________________________________________
```

**Figure 16 An example output from the CMM software**

# Uncertainties

# 7

**IN THIS CHAPTER**

- Uncertainty of measurement
- Co-ordinate measuring machine test uncertainty

When taking into account whether a CMM meets its specification, the uncertainty of measurement needs to be considered and ISO 14253-1 decision making rules applied. Appendix C gives an example taken from NPL Good Practice Guide No. 80 on how the decision rules are applied. But first the uncertainty has to be calculated. The sections below give some guidance on measurement uncertainty in general and some specifics relating to testing CMMs.

## Uncertainty of measurement

Uncertainty of measurement is covered in Bell S A *A beginner's guide to uncertainty in measurement* Measurement Good Practice Guide No. 11 (Issue 2), NPL, March 2001. If the reader is unfamiliar with measurement uncertainty it is advised they read this guide before reading the next section.

The definition of uncertainty is:

*parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand*

(BSI published document PD 6461-4:2004 General metrology. Practical guide to measurement uncertainty)

## Co-ordinate measuring machine test uncertainty

Uncertainties relating to the ISO 10360 tests are covered in DD ISO/TS 23165: 2006 *Geometrical product specifications (GPS). Guidelines for the evaluation of coordinate measuring machine (CMM) test uncertainty.* The main points are highlighted here.

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

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

Where $F$ is the form error reported on the calibration certificate of the test sphere and $u(F)$ is the standard uncertainty of the form error stated on the certificate.

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

$$u(E) = \sqrt{u^2(\varepsilon_{\mathrm{cal}}) + u^2(\varepsilon_{\alpha}) + u^2(\varepsilon_{\mathrm{t}}) + u^2(\varepsilon_{\mathrm{align}}) + u^2(\varepsilon_{\mathrm{fixt}})}$$

where

$\varepsilon_{\mathrm{cal}}$ is the calibration error of the material standard of size;
$\varepsilon_{\alpha}$ is the error due to the input of the CTE of the material standard of size;
$\varepsilon_{\mathrm{t}}$ is the error due to the input of the temperature of the material standard of size;
$\varepsilon_{\mathrm{align}}$ is the error due to the misalignment of the material standard of size; and

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

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:

$U(P) = k \times u(P)$ and $U(E) = k \times u(E)$

The value $k = 2$ shall be used.

Each term is fully explained in ISO/TS 23165. Worked examples can be found in Appendix C of the standard.

# Periodic reverification

# 8

**IN THIS CHAPTER**

- Length measurement error
- Single stylus probing error

It is recommended in ISO 10360 that a CMM be periodically reverified as part of an organization's internal quality assurance system. Reverification consists of carrying out the length measurement error and single stylus probing checks.

## Length measurement error

For periodic verification of the measurement error, the 1994 edition of the standard stated that the user shall substitute the error of indication $E$ with the error of indication chosen by the user $V$. The error of indication set by the user is based on the condition and age of the machine, the accuracy which it is required to achieve, the environmental conditions in which it operates, the user's requirements and use of the CMM.

The procedure and calculation detailed for the acceptance test should be carried out.

The performance of the CMM is reverified if the conditions detailed on page 33 - Interpretation of the results, are satisfied, when $V$ is substituted for $E$.

However, since 2001 the reverification test has been essentially the same as the acceptance test with the exception that the values applicable to $MPE_E$ and $MPE_P$ can be as stated by the customer.

With the 2009 edition of the standard the user is permitted to state the values of, and to specify detailed limitation applicable to, $E_{0,\ MPE}$, $R_{0,\ MPL}$ and $E_{150,\ MPE.}$

## Single stylus probing error

The single stylus probing error $P_{FTU,\ MPE}$ for periodic reverification is chosen by the user and is determined according to the user's requirements and the use of the CMM.

The procedure and calculation detailed for the acceptance test of the CMM probing systems should be carried out.

The CMM is verified if the single-stylus form error $P_{FTU}$ is not greater than the maximum permissible single-stylus form error $P_{FTU,\ MPE}$ as specified by the user. The uncertainty of measurement should be taken in to account according to ISO 14253-1.

If the probing system fails the reverification test, all probing equipment should be thoroughly checked for dust, dirt and any faults in the stylus system assembly (for example loose joints) that could be influencing the measurement results. Any faults should be corrected and the test repeated once only starting from the probing system qualification. It is also important that the qualification sphere, test sphere and stylus assembly are left for a suitable period of time after handling to reach thermal equilibrium.

# Interim check of the CMM

# 9

**IN THIS CHAPTER**

- Use of a purpose made test piece
- Use of a ball-ended bar
- A bar that can be kinematically located between a fixed reference sphere and the sphere of the CMM probe stylus
- A circular reference object (for example a ring gauge)
- Interim checks using a ball plate
- Interim checks and the comparison to specifications
- Interim probe check

Annex A of ISO 10360-2: 2009 strongly recommends that the CMM be checked regularly between periodic reverification. The user should determine the interval between checks according to the measurement performance required, the environmental operating conditions and the usage of the CMM.

The standard recommends that immediately after the performance verification test calibrated artefacts other than material standards of length be measured.

It is important that the CMM is also checked immediately after any significant event that could affect the performance of the machine, *e.g.,* struck by a forklift truck, impact loading, significant temperature change, high humidity, *etc*.

Probing strategies and speeds representative of those used in day-to-day measurements should be used in the interim check of the CMM. The material standard, the reference sphere and the stylus tip should be cleaned to remove all traces of dust particles before carrying out the test.

Typical reference objects recommended by the standard include:

- a purpose made test piece;
- a ball ended bar;
- a bar that can be kinematically located between a fixed reference sphere and the sphere of the CMM probe stylus;
- a circular reference object;
- a ball plate; and
- a hole plate.

The most relevant object should always be chosen.

The standard strongly recommends that the artefact has a coefficient of thermal expansion similar to that of typical workpieces measured on the CMM.

## Use of a purpose made test piece

Figure 17 shows a purpose made test piece. It is designed to duplicate the type of features and orientations that are routinely measured on the components being checked.

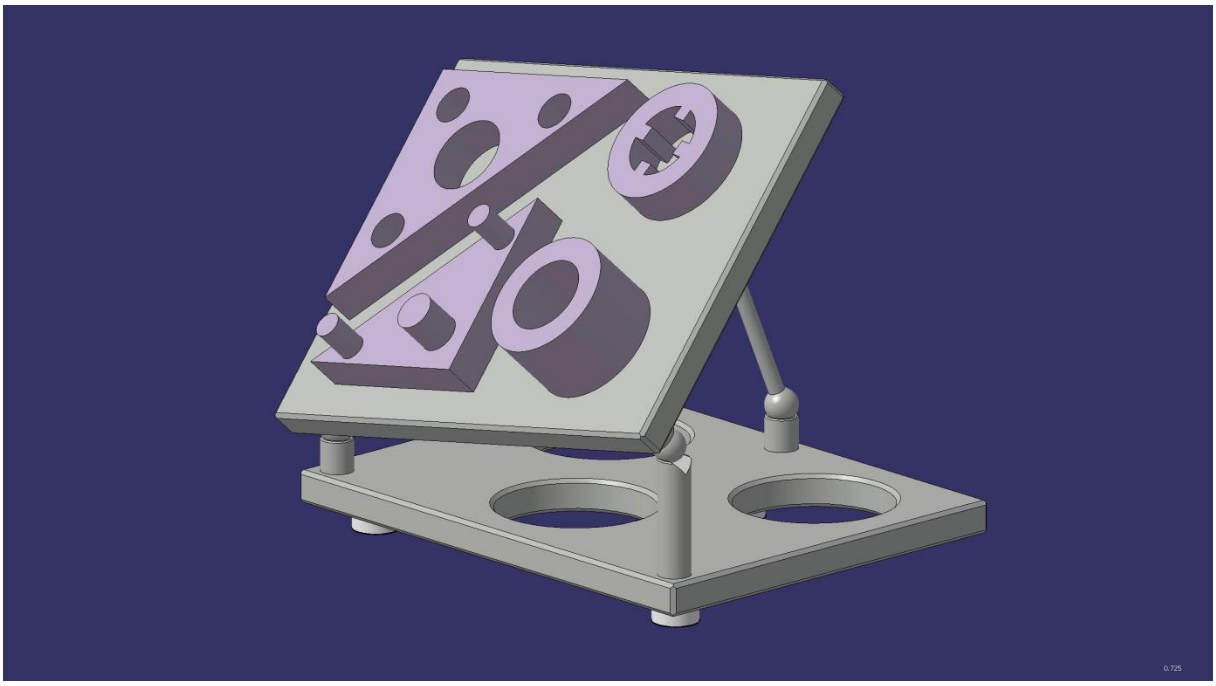


**Figure 17 A purpose made test piece with interchangeable top plate**

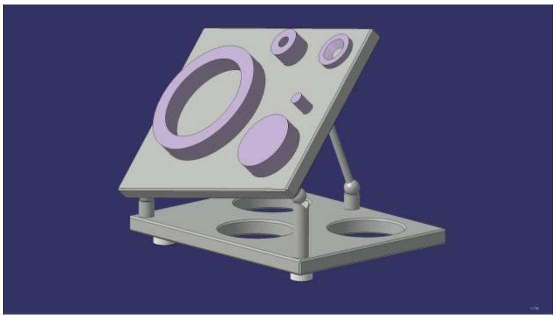


**Figure 18 Top plate with cylindrical artefacts**

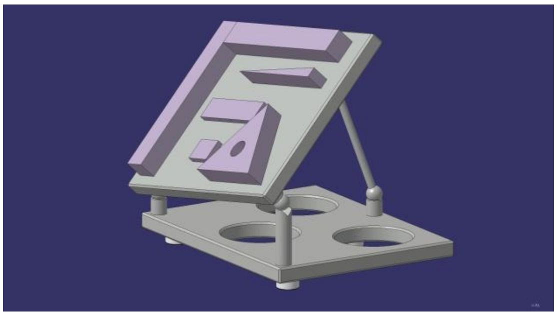


**Figure 19 A further range of artefacts**

Figure 18 and figure 19 show how the top plate is interchangeable to offer a different range of artefacts.

The advantages of purpose made test pieces are that they test more severely the capabilities of the CMM software used. Test pieces are used to test the machine in its normal working volume although with pallet systems this may mean that the artefact has to be repositioned several times. The disadvantages are that if the measurement task changes a new test piece may be needed. A further disadvantage is that the test piece may be difficult to make and measure to high accuracy and could be costly to calibrate

A high quality, calibrated replica of the item normally measured could also be used. High quality here means a surface finish and geometry that does not significantly affect the uncertainty of measurement. The item should also be dimensionally stable.

Figure 20 shows an alternative test piece made by a well-known CMM manufacturer. As shown in figure 21 and figure 22 it can be placed in the machine volume in a number of orientations. The test piece can be as simple as a typical part measured on the machine that is labelled and used only for CMM verification. It is suggested that the test piece is measured several times immediately after verification and then at regular intervals thereafter.

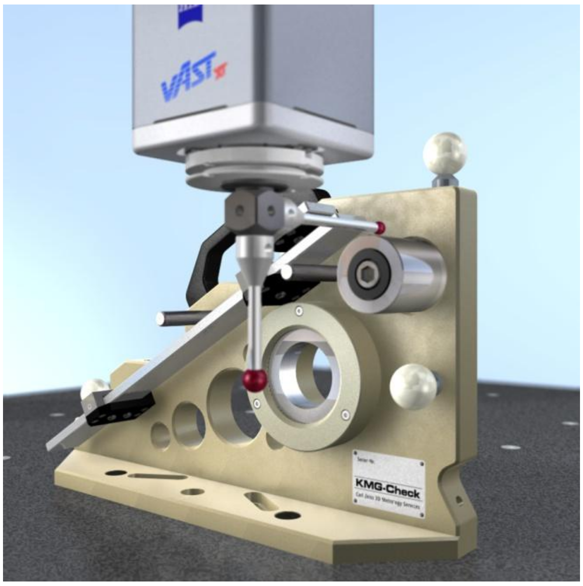



**Figure 20 CMM check artefact (©Carl Zeiss)**

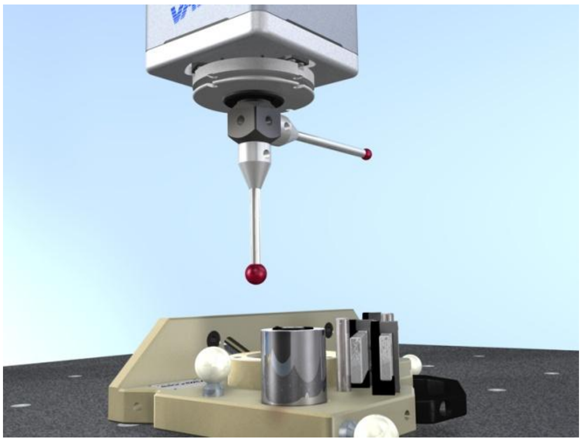


**Figure 21 CMM check artefact laid horizontally (©Carl Zeiss)**

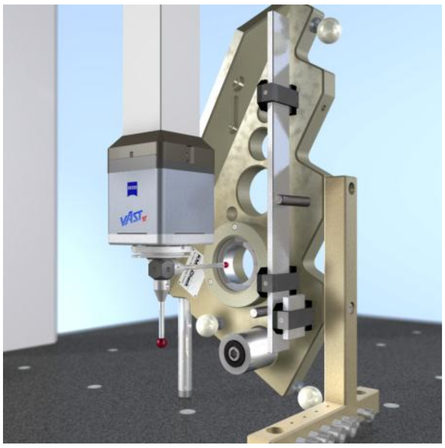


**Figure 22 CMM check artefact in a further orientation (©Carl Zeiss)**

## Use of a ball-ended bar

Ball bars (figure 23) were originally intended for manual air-bearing machines with the ball bar locked in the probe holder. A ball bar consists of two precision spheres mounted at either end of a long rigid bar. They are available in a range of lengths and may be adjustable.

**Figure 23 A selection of Ball Bars (©Bal-tec)**

**Figure 24 Free Standing ball Bar Kit (©Bal-Tec)**

The advantages of ball bars are that they are low cost to manufacture (high precision balls are available 'off-the-shelf'), portable, lightweight, compact and the use of a metal spacing rod makes them stable and robust. The main disadvantage of the ball bar is that its calibration is not directly traceable as it is based on a computed surface and not a real one. The other disadvantage is that it duplicates a measurement task seldom met in practice. The use of ball bars is also time-consuming due to the fact that they are fixed length and it should be noted that some composite bars are hygroscopic and dimensionally unstable.

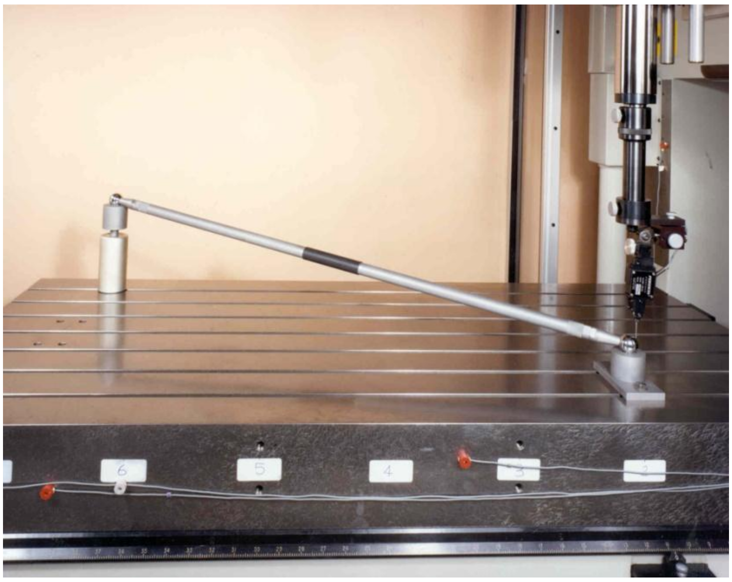


**Figure 25 An example of a ball-ended rod with magnetic cups for kinematic location**

## A bar that can be kinematically located between a fixed reference sphere and the sphere of the CMM probe stylus

ISO 10360 suggests as an interim check artefact a bar that can be kinematically located between a fixed reference sphere and the CMM probe-stylus sphere. Figure 26 shows one such implementation of this type of device - the Machine Checking Gauge (MCG) manufactured by Renishaw. The counterbalanced arm has a kinematic seat that sits on a precision ball on an adjustable tower. The seat allows accurate arm pivoting over a range of angles.

**Figure 26 Renishaw Machine Checking Gauge (Image © Renishaw plc 2011)**

The gauge consists of a baseplate, calibrated pivot, a range of six arms and a specially calibrated stylus (figure 27).

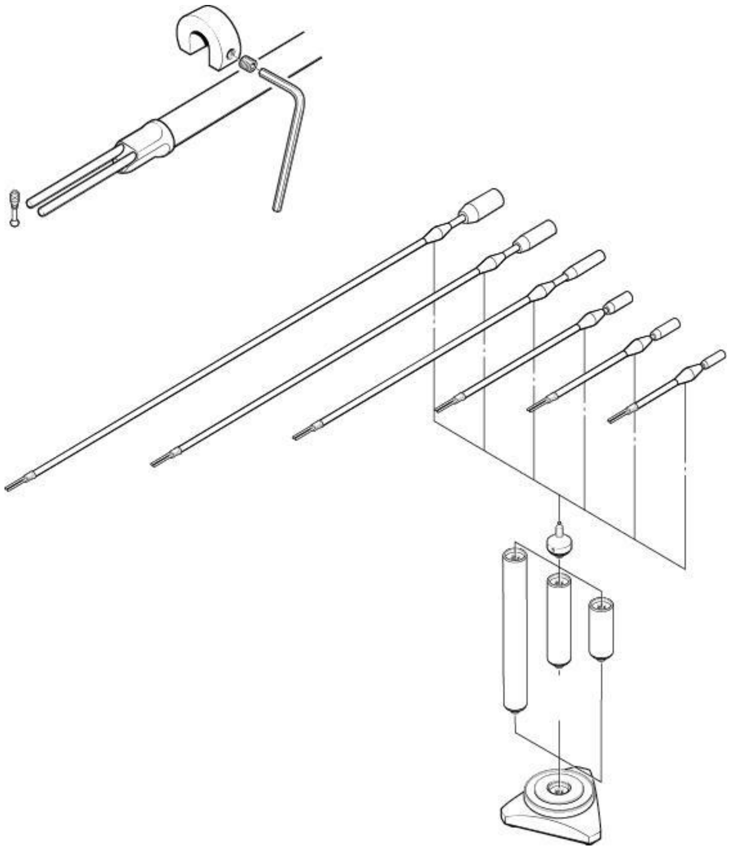


**Figure 27 Machine checking gauge – (Image © Renishaw plc 2011)**

The probe stylus slots into the end of what is in effect a reference ‘ball’ bar. The probe carries the bar with it over a spherical path and radial readings are taken at different positions. The range of these radial readings indicates the volumetric accuracy of the machine - this is the maximum error between any two points in any plane, over any distance within the full measuring range. Repetition of a sequence of readings will check the system’s repeatability and the total gauge error is claimed to be ± 0.5 μm. Checking time is typically fifteen minutes.

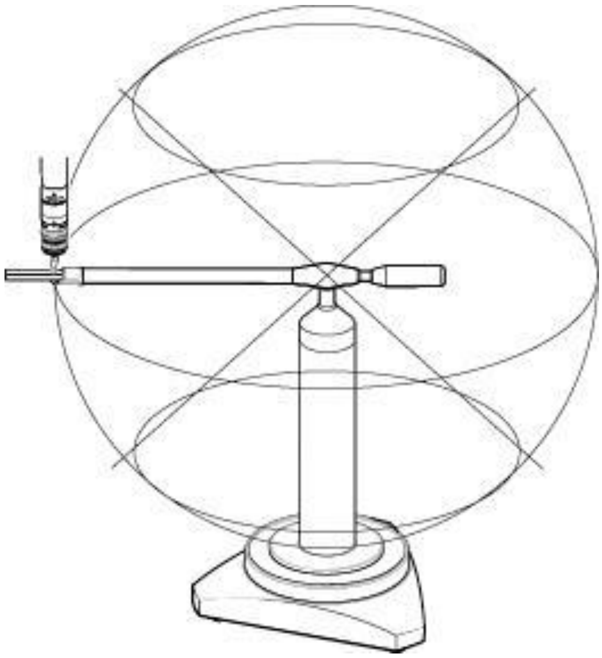


**Figure 28 Machine checking gauge envelope (Image © Renishaw plc 2011)**

The advantage of this type of device is that the various arm lengths can cover a large volume. It is also very portable, stable, lightweight, simple and quick to use and is normally available off-the-shelf. With suitable software it can be used as a diagnostic tool. For example, with the appropriate software it can provide information on volumetric accuracy, squareness and scale errors of the CMM.

The disadvantage is that it can only be used on machines that can vector in a circle, *i.e.* it may not be suitable for manual or older CNC machines. It is not as rugged as some of the other devices in the standard and it only tests one measuring task. It is also limited on its tests of the CMM software.

## A circular reference object (for example a ring gauge)

Ring gauges (or more correctly plain setting rings) may also be used as part of an interim check. The plain setting ring used should ideally comply with British Standard 4064/5:1966 *Specification for plain setting rings for use with internal diameter measuring machines*. Ideally this ring should be of a grade suitable for the CMM under test. Figure 29 shows a ring gauge being used to perform an interim check on a CMM.

**Figure 29 A ring gauge being used to perform an interim check on a CMM**

## Interim checks using a ball plate

Ball plates (figure 30) are relatively cheap to construct and can be as simple as an old surface plate on which off the shelf spheres are mounted. Ball plates are stable and very rugged. They do, however, have the disadvantage that they are very heavy. The ball plate shown in figure 30 takes two people to lift it on and off the machine. Again the measurement task is one that is not met often in practice and it does rely on good software to compute the ball centres. As ball centres are being measured this artefact will not discover probe qualification related problems unless the balls have been calibrated for size. A commercially available ball plate that can be accessed from both sides is shown in figure 31.

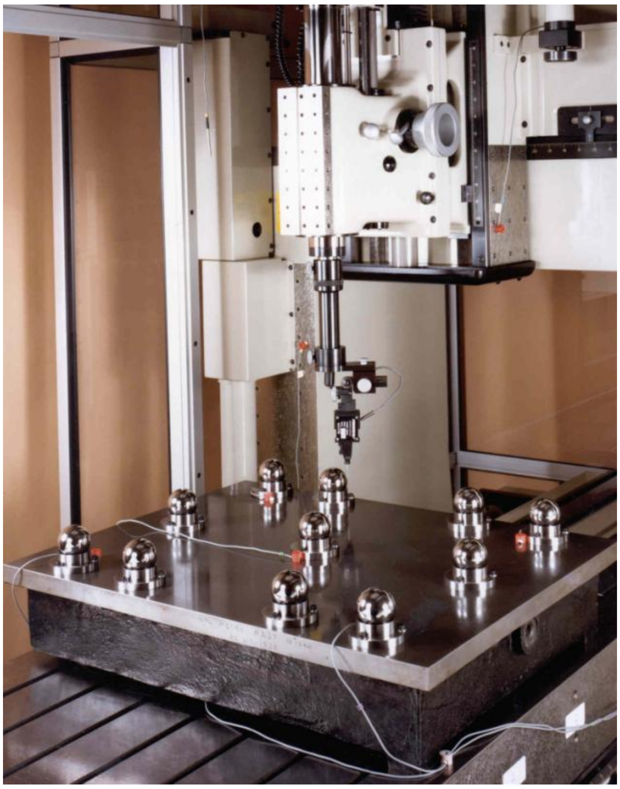


Figure 30 A fabricated ball plate

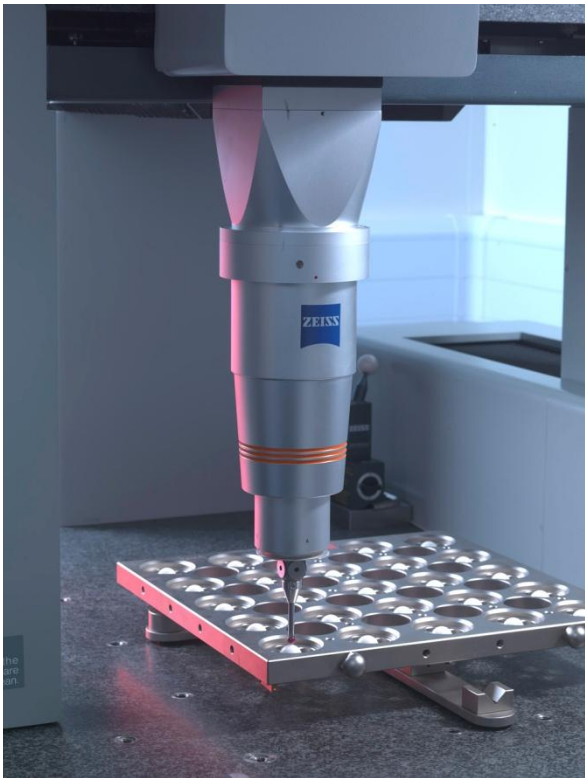


Figure 31 A commercial ball plate

## Interim checks using a hole plate

A hole plate such as that shown in figure 32 can be measured in various orientations. It has the advantage that it can be accessed from either side and tends to be lighter than a ball plate of similar size. Figure 33 shows a hole plate made of a low CTE material.

Figure 32 A hole plate being used to check a CMM

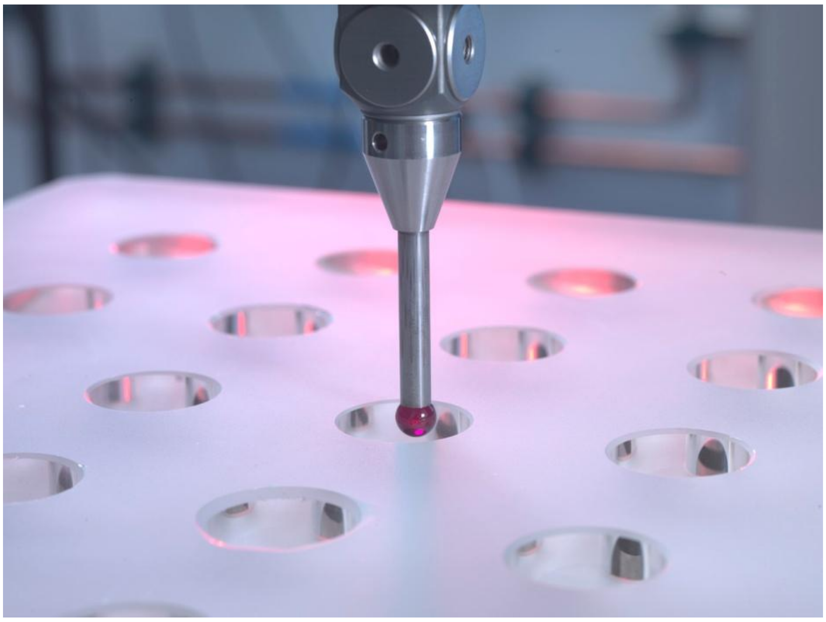


**Figure 33 A glass hole plate**

## Interim checks and the comparison to specifications

In some cases, the user may wish to perform an interim test such that the results can be compared to the manufacturer's specifications for $E_{0,\ \mathrm{MPE}}$, $R_{0,\ \mathrm{MPL}}$ and $E_{\mathrm{L},\ \mathrm{MPE}}$. In this case, a calibrated test length, should be used and the measurement procedures described in ISO 10360 followed.

In order to minimize the time to perform the interim test an abbreviated test procedure can be carried out and it is suggested that this procedure should focus on those test positions that most commonly reveal a problem with the CMM. An example would be the measurement of a single long test length in each of the body diagonals. This test will generally reveal CMM errors more so than the measurements of five test lengths along a CMM axis.

Each of the errors of indication from the interim test should be less than the corresponding specification, *e.g.* $E_{0,\ \mathrm{MPE}}$, provided the test is conducted according to the procedures stated in ISO 10360 and the environmental conditions are within those stated by the manufacturer.

## Interim probe check

Interim probe checking should be carried out in accordance with the test procedure and calculation of results used in the Acceptance Test of the CMM Probing System detailed in chapter 6.

ISO 10360-2: 2001 strongly recommends that different probe strategies adopted by the user such as multiple styli, the use of stylus extensions, approach direction and speeds are checked regularly between periodic reverification. This idea is extended in ISO10360-5: 2010.

The interim check is essentially a repeat of the main tests but with reduced extent in terms of the number of measuring points being assessed. It is, however, recommended that the probing system be checked regularly and particularly after any incident which could significantly affect the probing performance.

# Improving measurement confidence

# 10

**IN THIS CHAPTER**

- Similarity conditions
- An example

In addition to performing a verification test there are other ways in which users can gain extra confidence in the measurements they are making with a CMM. One way requires the user to adopt task-related calibration strategies in which the measurement of traceable artefacts is used to indicate the errors associated with specific measurement tasks (ISO/TS 15530-3: 2004 *Geometrical Product Specifications (GPS) — Coordinate measuring machines (CMM): Technique for determining the uncertainty of measurement — Part 3: Use of calibrated workpieces or standards*). Calibrations of this kind are only valid for the inspection of workpieces with essentially the same geometrical form and size as the calibrated object, measured in the same orientation and location, and using the same probing and measurement strategy.

## Similarity conditions

The use of calibrated workpieces requires that the following similarity conditions be observed:

- dimensions within 25 mm below 250 mm and within 10 % above 250 mm;
- angles within ± 5°;
- form deviations, surface texture and material should be similar;
- measurement strategy should be identical;
- probe configuration should be identical; and
- position and orientation should be similar.

The measurement procedure of the reference artefact and the actual measurement should be the same. Conditions to consider are, for example, handling, exchange and clamping, time elapsed between probing points, loading and unloading procedures, measuring force and speed. In addition the environmental conditions (including all variations) during measurement of the reference artefact and actual measurement should be considered. Conditions to consider include temperature, temperature stabilisation time and temperature corrections (if used).

## An example using a calibrated workpiece

An example of such a procedure to improve measurement confidence, involving the measurement of a deep bore with a long stylus, is as follows:

1. Perform a probing system qualification as normal.
2. Measure the reference artefact (in this case a plain setting ring) - figure 34.

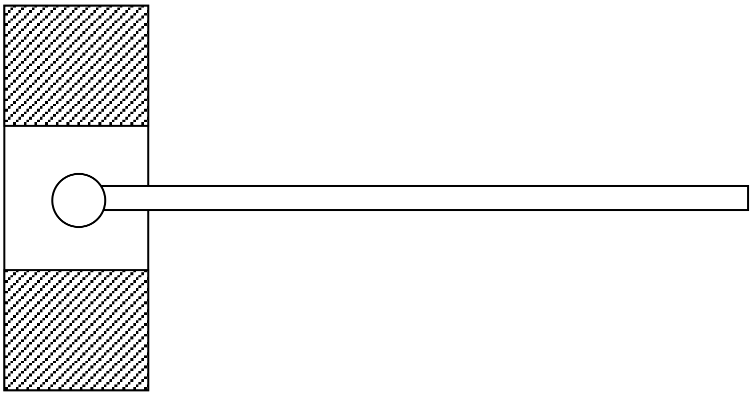


**Figure 34 Reference artefact (plain setting ring)**

3. Measure the component (in this case a long tube) - figure 35.

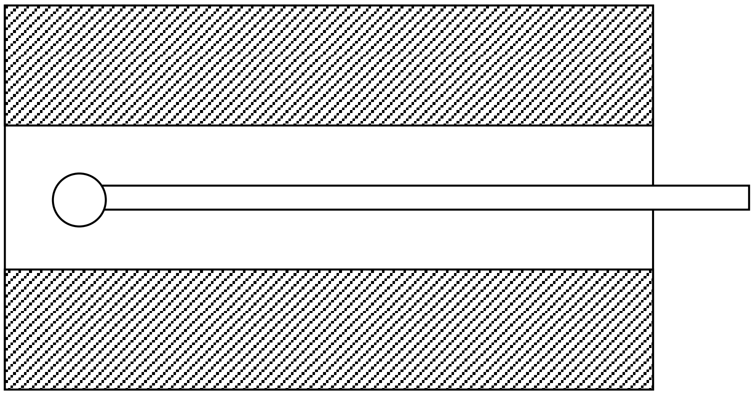


**Figure 35 Component – a long tube**

4. Repeat the measurement of the reference artefact.

Use the same procedure at each stage in the process, *i.e.* programme, probe set up, direction of approach and speed. As in the example above it is recommended that the user measure the reference artefact before and after the object(s) to be inspected.

If the results of the measurement of the ring gauge in the above example agree with its calibrated size to within the combined uncertainties of the machine and the ring calibration then it has been demonstrated that no degradation in accuracy has resulted from the choice of stylus. If a difference between the calibrated size of the ring and the measured size is noted, and this difference is repeatable it may be possible to correct measurements made on the tube. For example, if measurements made on the ring gauge are consistently large by 0.010 mm the 0.010 mm can be subtracted from all diameter measurements made on the component.

Because of the complex error structure inherent in CMMs, procedures of this kind are only valid for objects with the same geometrical form and size as the reference artefact used, measured in the same location and using the same measurement strategy. Provided that suitable reference artefacts are available this type of approach to measurement can achieve high accuracy with relatively little effort.

Where a user is involved in measuring the same geometric form on a number of components the measuring strategy would involve assessing the error sources associated with that type of inspection in one particular part of the working volume of the CMM. However, if the components were to be measured at different locations in the working volume then a much more rigorous evaluation of the variation in measuring capability with position would have to be undertaken to indicate whether the position and orientation of the component would effect the accuracy of the result.

This idea is extended further in ISO/TS 15530-3: 2004 *Geometrical Product Specifications (GPS) — Coordinate measuring machines (CMM): Technique for determining the uncertainty of measurement* -- *Part 3: Use of calibrated workpieces or standards* where the information is used to calculate measurement uncertainties.

# CMMs using multiple stylus probing systems

# 11

**IN THIS CHAPTER**

- Fixed multi-probe and multi-stylus probing systems
- Articulating probing systems

SO far only the single-stylus probing error has been covered when referring to ISO 10360-5. The tests described in part 5 of ISO 10360 are also applicable to CMMs that use more than one stylus or stylus orientation when measuring a workpiece. Experience has shown that the errors as calculated in accordance with part 5 of the standard for multiple probing systems are significant and, at times the dominant errors in the CMM. However, due to the virtually infinite variety of probing system configurations on modern CMMs the tests as defined are limited to only providing a format for testing. The tests are intended to provide information about the ability of a CMM to measure a feature or features using multiple styli, probes, or articulated-probe positions.

The tests are applicable to situations such as:

- multiple styli connected to the CMM probe, *e.g.* a star;
- installations using an articulating probing system (motorised/automatic or manual) that can be pre-qualified;
- installations using a repeatable probe changing system;
- installations using a repeatable stylus changing system; and
- multiple probe installations.

The procedure will be helpful in minimising uncertainty components of the probing system for specific measuring tasks. The user can reduce errors by removing contributing elements (*e.g.* long extensions, long styli) and re-testing the new configuration set. The test described in part 5 of the standard is sensitive to many errors attributable to both the CMM and the probing system.

The tests detailed in ISO 10360: 5 are performed in addition to the length-measuring test according to ISO 10360-2 that is conducted using only one stylus.

## Fixed multi-probe and multi-stylus probing systems

ISO 10360 part 5 introduces the concept of the multi-stylus probing errors. The principle of this test procedure is to measure the form, size and location of a test sphere using five different fixed styli.

If a stylus or probe changing system is supplied with the CMM, five changes are performed, one before each stylus is used. For each group of twenty-five points taken with a single stylus, a least-squares sphere fit is associated with the points, for a total of five sphere fits. The ranges of the centre coordinates ($X$, $Y$ and $Z$) of all five spheres are calculated. In addition, a least-squares sphere fit using all 125 points is examined for the form and size errors of indication.

## Articulating probing systems

Part 5 also details a similar test for articulating probing systems. The principle is to measure the form, size and location of a test sphere using five different angular positions of the articulating probing system. At each angular position, twenty-five points are measured on the test sphere, a total of 125 points using all five positions. Since the results of these tests are highly dependent on the probe-tip-offset length, a series of tip offset lengths needs to be considered. Sample lengths are given in the standard.

# Assessment and reverification tests for CMMs with the axis of a rotary table as the fourth axis

# 12

**IN THIS CHAPTER**

- Requirements for rotary tables
- Acceptance and reverification tests

Rotary tables are used on CMMs for a number of types of measurements, these include the measurement of gears, brake drums, spline drives and where the user requires the stylus tip to remain in a static position whilst the workpiece is orientated in a rotational sense.

ISO 10360-3: 2000 *Geometrical Product Specifications (GPS) – Acceptance and reverification tests for coordinate measuring machines (CMM)—Part 3: CMMs with the axis of a rotary table as the fourth axis* specifies the acceptance and reverification test which verifies that the performance of a four axis CMM is in accordance with that stated by both the manufacturer and the user.

## Requirements for rotary tables

### *Error of indication*

The errors of indication are designated FR, FT and FA and are expressed in micrometres. FR is the radial four-axis error; FT is the tangential four-axis error and FA the axial four-axis error.

These errors, which shall not exceed the maximum permissible errors $MPE_{FR}$, $MPE_{FT}$ and $MPE_{FA}$ are expressed in micrometres and are:

- as stated by the manufacturer for the acceptance test; and
- as stated by the user for the reverification test.

### *Environmental conditions*

Limits that govern temperature conditions, air humidity and vibration at the installation site are specified by:

- the manufacturer for the acceptance test; and
- the user for the reverification test.

In both cases, the user is free to specify the conditions within the specified limits.

### *Stylus system*

The limits placed on the stylus configuration to which the stated values of $MPE_{FR}$, $MPE_{FT}$ and $MPE_{FA}$ apply are specified by:

- the manufacturer for the acceptance test; and
- the user for the reverification test.

In both cases the user is free to select the stylus system within the specified limits.

### *Operating conditions*

The CMM should be operated using the procedures described in the manufacturers operating manual for

1. machine start up/warm up cycles;

2. stylus system configuration;

3. cleaning procedures for stylus tip and reference sphere; (The stylus tip and reference sphere should be cleaned before the probing system qualification. The cleaning process should not leave a residual film that could affect the measuring or test result.)

4. probing system qualification; and

5. rotary table set up and qualification.

## Acceptance and reverification tests

### *Principles*

The principle of the assessment is to establish whether the CMM is capable of measuring within the stated maximum permissible errors by determining the variation of the measured co-ordinates of the centres of two spheres mounted on the rotary table.

The centre of each test sphere is measured with a series of measurements at different angular positions of the rotary table. Each test sphere centre is determined in three directions: radial, tangential and axial.

The errors of indication are calculated for each test sphere as the range between the maximum and minimum measurement results for each of the three directions.

### *Measuring equipment*

Two test spheres with certified form designated A and B, whose diameters should be not less than 10 mm and not greater than 30 mm are used. The diameters of the spheres need not be calibrated since only the centres of the spheres are used to determine the three four-axis errors. The spheres must be mounted rigidly to the rotary table to avoid errors due to bending.

### *Set up and procedure*

The test spheres should be mounted on the rotary table in accordance with table 9 (see Figure 1 of ISO 10360-3: 2000 for an illustration of this set-up).

**Table 9 Location of the test spheres on the rotary table**

| Combination Number | Height difference $\Delta h$ mm | Radius $r$ mm |
|---|---|---|
| 1 | 200 | 200 |
| 2 | 400 | 200 |
| 3 | 400 | 400 |
| 4 | 800 | 400 |
| 5 | 800 | 800 |

The values in table 9 are default values. The manufacturer must specify one of the above combinations. Other values may be used with agreement between the user and manufacturer.

Test sphere A should be positioned as close to the rotary table surface as possible at a radius *r*.

Test sphere B should be approximately at the same radius *r* and approximately diametrically opposite to the test sphere A, but higher from the table surface by an amount $\Delta h$.

The user should define a Cartesian workpiece co-ordinate system on the rotary table that meets the following conditions:

1. the centre of the test sphere B establishes the origin;
2. the primary axis, which defines the axial direction, shall be parallel to the axis of the rotary table; and
3. the secondary axis, which defines the radial direction, shall lie in the plane that contains the primary axis and the centre of the test sphere A.

The user should begin the test by measuring test sphere B in its original position (position 0). The angular position should be any position other than the zero reading on the rotary table.

The rotary table is rotated through a series of seven angular positions, and the test sphere A is measured in each position.

ISO 10360-3: 2000 recommends that the positions of the seven angular positions extend at least 720$^{\circ}$ from the start position.

The rotary table is now rotated in the opposite direction to seven angular positions and the test sphere A is once again measured at each position.

The rotary table is returned to its original position and both test spheres should be measured (position 14).

The rotary table is now rotated in the same direction to seven different angular positions and then rotated in the opposite direction to seven angular positions. The test sphere B is measured at each position. On returning the rotary table to its original position both test spheres are now measured (position 28), see table 10.

**Table 10 Default nominal angular positions for rotary table test**

| *Position* Number | Angular position degrees | | Measured co-ordinates for | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Test sphere A | | | Test sphere B | | |
| | $W_1$ | $W_2$ | $X_A$ | $Y_A$ | $Z_A$ | $X_B$ | $Y_B$ | $Z_B$ |
| 0 | 0 | 0 | $X_{A0}$ | $Y_{A0}$ | $Z_{A0}$ | $X_{B0}=0$ | $Y_{B0}=0$ | $Z_{B0}=0$ |
| 1 | 75 | 135 | $X_{A1}$ | $Y_{A1}=0$ | $Z_{A1}$ | - | - | - |
| 2 | 125 | 225 | $X_{A2}$ | $Y_{A2}$ | $Z_{A2}$ | - | - | - |
| 3 | 175 | 315 | $X_{A3}$ | $Y_{A3}$ | $Z_{A3}$ | - | - | - |
| 4 | 385 | 405 | $X_{A4}$ | $Y_{A4}$ | $Z_{A4}$ | - | - | - |
| 5 | 410 | 540 | $X_{A5}$ | $Y_{A5}$ | $Z_{A5}$ | - | - | - |
| 6 | 510 | 630 | $X_{A6}$ | $Y_{A6}$ | $Z_{A6}$ | - | - | - |
| 7 | 820 | 810 | $X_{A7}$ | $Y_{A7}$ | $Z_{A7}$ | - | - | - |
| 8 | 510 | 630 | $X_{A8}$ | $Y_{A8}$ | $Z_{A8}$ | - | - | - |
| 9 | 410 | 540 | $X_{A9}$ | $Y_{A9}$ | $Z_{A9}$ | - | - | - |
| 10 | 385 | 405 | $X_{A10}$ | $Y_{A10}$ | $Z_{A10}$ | - | - | - |
| 11 | 175 | 315 | $X_{A11}$ | $Y_{A11}$ | $Z_{A11}$ | - | - | - |
| 12 | 125 | 225 | $X_{A12}$ | $Y_{A12}$ | $Z_{A12}$ | - | - | - |
| 13 | 75 | 135 | $X_{A13}$ | $Y_{A13}$ | $Z_{A13}$ | - | - | - |
| 14 | 0 | 0 | $X_{A14}$ | $Y_{A14}$ | $Z_{A14}$ | $X_{B14}$ | $Y_{B14}$ | $Z_{B14}$ |
| 15 | -75 | -135 | - | - | - | $X_{B15}$ | $Y_{B15}$ | $Z_{B15}$ |
| 16 | -125 | -225 | - | - | - | $X_{B16}$ | $Y_{B16}$ | $Z_{B16}$ |
| 17 | -175 | -315 | - | - | - | $X_{B17}$ | $Y_{B17}$ | $Z_{B17}$ |
| 18 | -385 | -405 | - | - | - | $X_{B18}$ | $Y_{B18}$ | $Z_{B18}$ |
| 19 | -410 | -540 | - | - | - | $X_{B19}$ | $Y_{B19}$ | $Z_{B19}$ |
| 20 | -510 | -630 | - | - | - | $X_{B20}$ | $Y_{B20}$ | $Z_{20}$ |
| 21 | -820 | -810 | - | - | - | $X_{B21}$ | $Y_{B21}$ | $Z_{21}$ |
| 22 | -510 | -630 | - | - | - | $X_{B22}$ | $Y_{B22}$ | $Z_{B22}$ |
| 23 | -410 | -540 | - | - | - | $X_{B23}$ | $Y_{B23}$ | $Z_{B23}$ |
| 24 | -385 | -405 | - | - | - | $X_{B24}$ | $Y_{B24}$ | $Z_{B24}$ |
| 25 | -175 | -315 | - | - | - | $X_{B25}$ | $Y_{B25}$ | $Z_{B25}$ |
| 26 | -125 | -225 | - | - | - | $X_{B26}$ | $Y_{B26}$ | $Z_{B26}$ |
| 27 | -75 | -135 | - | - | - | $X_{B27}$ | $Y_{B27}$ | $Z_{B27}$ |
| 28 | 0 | 0 | $X_{A28}$ | $Y_{A28}$ | $Z_{A28}$ | $X_{B28}$ | $Y_{B28}$ | $Z_{B28}$ |
| | | | | | | | | |
| Four-axis errors | | | $FR_A$ | $FT_A$ | $FA_A$ | $FR_B$ | $FT_B$ | $FA_B$ |

Note:

1. Angular position W1 applies to CMMs with partial coverage of the rotary table.
2. Angular position W2 applies to CMMs with full coverage of the rotary table.
3. Only one of these columns applies to a specific machine being tested.
4. A dash (–) means that no measurement is taken at that location of that test sphere in that angular position.

### Results

Using measurements from positions 0 to 28, the three four-axis errors (FR, FT and FA) as the peak-to-peak variation of each of the radial, tangential and axial co-ordinates respectively of both test sphere centres are computed.

$X_A$ and $X_B$ are the radial components of spheres A and B and are used to calculate the radial four-axis error $FR_A$ and $FR_B$.

$Y_A$ and $Y_B$ are the tangential components of spheres A and B and are used to calculate the tangential four-axis error $FT_A$ and $FT_B$.

$Z_A$ and $Z_B$ are the axial components of spheres A and B and are used to calculate the axial four-axis error $FA_A$ and $FA_B$.

### Compliance with specifications

*Acceptance test*

The performance of the CMM and rotary table is verified if none of the four-axis errors ($FR_A$, $FT_A$, $FA_A$, $FR_B$, $FT_B$ and $FA_B$) are greater than the three maximum permissible errors ($MPE_{FR}$, $MPE_{FT}$ and $MPE_{FA}$) as specified by the manufacturer.

*Reverification test*

The performance of the CMM and rotary table is verified if none of the four-axis errors ($FR_A$, $FT_A$, $FA_A$, $FR_B$, $FT_B$ and $FA_B$) are greater than the three maximum permissible errors ($MPE_{FR}$, $MPE_{FT}$ and $MPE_{FA}$) as specified by the user.

*Interim check*

A reduced reverification test may be used periodically to demonstrate the probability that the CMM will conform to specified requirements regarding the three maximum permissible errors. The reverification test may be reduced in the following areas, number of test spheres, number of angular positions and number of measurements performed

If a rotary table is fixed to the CMM the acceptance test may be sufficient to quantify all errors related to all machine axes. It will not be necessary to check all linear axes, if the performance of the machine is verified for FR, FT and FA as all axes must be in good working order.

# Verification of large CMMs

# 13

**IN THIS CHAPTER**

- Artefacts for verification of large CMMs
- Use of laser interferometers

The techniques described in this guide and, before the latest revision, in ISO 10360 are mainly applicable to CMMs with operating axes of 1 m or less.

## Artefacts for verification of large CMMs

Before the use of laser interferometer systems was allowed in ISO 10360 the verification of larger CMMs was hindered by the limited availability of suitable artefacts. One suitable artefact was detailed in Corta, R, Cox, M G, Cross, N R, Dotson, J R, Flack, D R, Forbes, A B, O'Donnell, J, Peggs, G N, Prieto, E *A large reference artefact for CMM verification* CLM 6, NPL, May 1998. This report describes the design, construction and calibration of a large reference artefact suitable for use in the verification of large CMMs. The artefact is of modular design, constructed in 1 m and 0.5 m tubular sections made from carbon-composite materials. Each section can carry a range of reference surfaces including reference spheres (tooling balls). Three metrology laboratories using a repositioning methodology have calibrated the artefact. Equipment for supporting the artefact during the verification of a CMM has also been designed and constructed. The artefact and positioning equipment have been successfully tested in the verification of two large CMMs according to the principles of IS0 10360-2. The design philosophy and calibration methodology are flexible and can be easily adapted, providing a practical approach to large CMM verification.

Further information can also be found in the final and synthesis reports for contract MAT1-CT94-0012 entitled Calibration of Large Artefacts.

Other work has also been carried out at NIST and PTB on methods for the evaluation of large CMMs. The NIST method is described in S. D. Phillips, D. Sawyer, B. Borchardt, D. Ward, D. E. Beutel, 2001 *A novel artefact for testing large coordinate measuring machines* Precision Eng., **25** (1).

## Use of laser interferometers

ISO 10360 now allows the use of laser interferometers, a useful tool for checking larger machines (figure 36 and figure 37). The laser interferometer is considered to be a low CTE calibrated test length and so the measurement of a normal CTE calibrated test length is required by the standard.

**Figure 36 Checking a large CMM with a tracking interferometer (Image © Etalon Ag)**

It is good practice to measure the normal CTE artefact along a measurement line that was previously measured using the interferometer. The consistency of the errors of indication from the laser interferometer and the normal CTE artefact serves as a check that refractive index corrections and compensation of the artefact CTE are being implemented correctly.

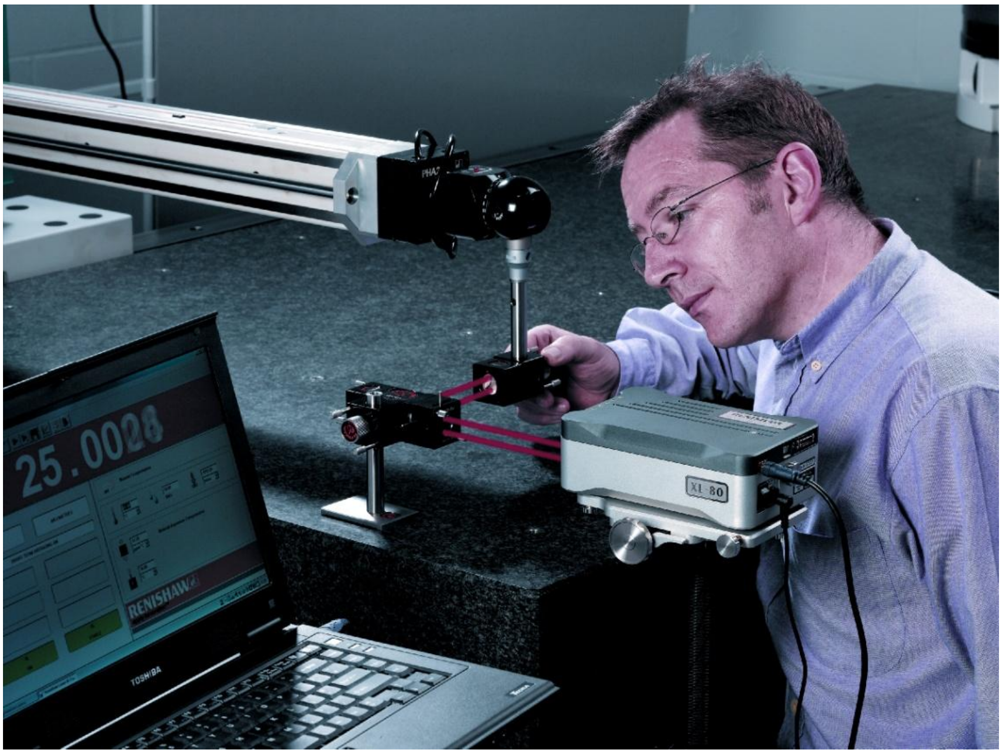



**Figure 37 Checking a large CMM with an interferometer (Image © Renishaw plc 2011)**

Good practice in the use of interferometers is covered in Flack, D R, Hannaford, J *Fundamental Good Practice in Dimensional Metrology* NPL Measurement Good Practice Guide No. 80.

# Summary

# 14

**IN THIS CHAPTER**

- Summary

This measurement good practice guide has provided an overview of the ISO 10360 series of standards. The key good practice guidelines for carrying out CMM performance verification can be summarised as follows:

- CMM to be verified to ISO 10360-2 and ISO 10360-5;
    - acceptance test
    - reverification test
    - interim check (during the periods between periodic reverification)
- carry out the probe test first (See Annex B of ISO 10360-5);
- be aware of the distinction between the test sphere and reference sphere;
- make sure everything is clean;
- use the correct symbols and terminology;
- allow plenty of time for items to reach thermal equilibrium with the environment;
- be aware if the distinction between uni-directional and bi-directional measurements;
- be aware of the coefficient of thermal expansion;
- part 3 of the standard applies to machines with rotary tables;
- part 4 relates to scanning (not covered in this guide);
- part 5 applies to machines with multiple probing systems;
- large CMMs may present special problems;
- be aware of the various editions of the standard;
- ISO 10360-2 does not explicitly apply to non-Cartesian CMMs however it may be applied to non-Cartesian CMMs by mutual agreement;
- be aware of DD ISO/TS 23165: 2006 and test uncertainty; and
- be aware of the limitations of the test.

# Glossary of terms

# 15

**IN THIS CHAPTER**

- A glossary of terms.

## Glossary of terms

Terms defined below are based on the VIM, 3rd edition, JCGM 200:2008 (*International Vocabulary of Metrology - Basic and General Concepts and Associated Terms*) and ISO 10360 Parts 1 and 2.

| | |
|---|---|
| Accreditation | The formal recognition that a calibration laboratory is competent to carry out specific calibrations. |
| Acceptance test | The set of operations agreed upon by CMM manufacturer and user to verify the performance of a CMM as stated by the manufacturer. |
| Ball-ended bar | A gauge consisting of two spheres of the same nominal diameter mounted at the ends of a connecting rigid bar. |
| Ball plate | A mechanical artefact comprising a number of spheres mounted in fixed positions on the plate, usually in a single plane. |
| CMM | A measuring system with the means to move a probing system and capability to determine spatial coordinates on a workpiece surface. |
| Error of indication of a CMM | The indication of a CMM minus the (conventional) true value of the measurand. |
| Gauge block | Material measure of rectangular section, made of wear-resistant material, with one pair of planar, mutually parallel measuring faces, which can be wrung to the measuring faces of other gauge blocks to make composite assemblies, or to similarly finished surfaces of auxiliary plates for length measurements. |
| Geometric errors | The departures from the ideal geometry caused by a lack of mechanical perfection in the moving elements of the CMM.<br><br>Note The most commonly encountered geometrical errors include: roll, pitch, yaw, straightness in both the horizontal and vertical orientations and positioning error, in each axis; there are also squareness errors between pairs of axes. |

| | |
|---|---|
| Hole plate | A mechanical artefact that comprises a flat plane pierced with holes whose axes are normal to one of the surfaces. |
| Indication of a CMM | The value of a measurand provided by the CMM. |
| Interim check | Test specified by the user and executed between reverifications to maintain the level of confidence in the measurements taken on the CMM. |
| Length bar | A cylindrical type mechanical artefact with a accurately known length between its two flat parallel ends. |
| Length measurement error | Error of indication when measuring a calibrated test length using a CMM with a ram axis stylus tip offset of L, using a single probing point (or equivalent) at each end of the calibrated test length |
| Material standard | Material measure reproducing a traceable value of a dimensional quantity of a feature |
| Material standard of size | Material standard reproducing a feature of size |
| Material standard of length | Material standard containing two or more nominally parallel planes, the distance between these planes being specified. |
| Probing error | Error of indication with in which the range of radii of a spherical material standard of size can be determined by a CMM, the measurements being taken in a discrete-point probing mode using one stylus on a test sphere. |
| Probing system qualification | Establishment of the parameters of a probing system necessary for subsequent measurements. |
| Reversal method | A method utilising the measurement of a component and subsequent re-measurement of the component in a different orientation which is designed to cancel out errors associated with the measurement system and reveal errors associated with the component. |

| | |
|---|---|
| Reverification test | Test to verify that the performance of a CMM is as stated by the user and executed according to the same procedure as those for the acceptance test. |
| Reference sphere | Spherical material standard of size placed within a measuring volume of a CMM for the purpose of probing system qualification. |
| Task-related calibration | The set of operations which establish, under specified conditions, the relationship between values indicated by a CMM and the corresponding known values of a limited family of precisely defined measurands which constitute a subset of the measurement capabilities of a CMM. |
| Test sphere | A spherical material standard of size used for acceptance test and reverification test. |

# Health and safety

# 16

**IN THIS CHAPTER**

- Mechanical
- Hazards associated with laser illumination
- Chemical

When checking a machine for compliance to ISO 10360 any local safety rules should be adhered to and a risk assessment undertaken before starting the work. If working at a customer's site be aware of any evacuation procedures and any extra risks such as moving vehicles and overhead cranes. Some specific things to look for when carrying out a risk assessment are listed below.

## Mechanical hazards

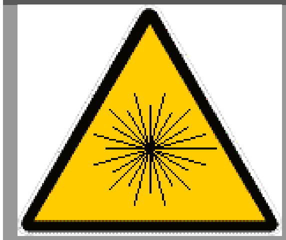
Many of the length standards mentioned in this guide are relatively heavy. The appropriate lifting techniques and equipment should always be used and safety shoes worn. Operators should wear laboratory coats or overalls for safety reasons and to prevent fibres shed from clothing from falling on items being measured.

Machines under direct computer control may move without warning. The operator should stand back from the machine during an automatic run.

## Hazards associated with laser illumination

The standards now allow the use of laser interferometers. It goes without saying that any users of laser interferometers should be trained in their safe usage. Some general guidance is given in the box below.

**NOTE**



**Important safety information**
A rough guide to laser safety stickers would say that any laser system with a visible output of less than 0.2 mW is considered a Class 1 laser and is not dangerous. While any visible laser of between 0.2 mW and 1.0 mW output power is considered a Class 2 and relies on sensible people blinking before any damage is done to their vision. Class 3B refers to power levels above 5.0 mW and can cause damage to your retina and should on the whole be treated with a great deal of respect because once damaged your eyes are irreparable and irreplaceable! Class 4 involves powers above 0.5 W and will blind you, burn holes through your hand and generally ensure that you have a really bad day. (For a more detailed description of the classes have a look at BS EN 60825-1 2007.)

## Chemical hazards

Chemicals may need to be used for cleaning purposes. Make sure the manufacturer's safety guidance is followed and the relevant personal protective equipment worn. Substances may be covered by the COSHH regulations.

# Appendices

# 17

**IN THIS CHAPTER**

- Appendix A Links to other useful sources of information.
- Appendix B Further reading.

# Appendix A Links to other useful sources of information

## A.1 National and International Organisations

### A.1.1 National Physical Laboratory

*"When you can measure what you are speaking about and express it in numbers you know something about it; but when you can not express it in numbers your knowledge is of a meagre and unsatisfactory kind."*

Lord Kelvin, British Scientist (1824 – 1907)

The National Physical Laboratory (NPL) is the UK's national measurement institute and is a world-leading centre of excellence in developing and applying the most accurate measurement standards, science and technology available. For more than a century NPL has developed and maintained the nation's primary measurement standards. These standards underpin an infrastructure of traceability throughout the UK and the world that ensures accuracy and consistency of measurement.

NPL ensures that cutting edge measurement science and technology have a positive impact in the real world. NPL delivers world-leading measurement solutions that are critical to commercial research and development, and support business success across the UK and the globe.

Good measurement improves productivity and quality; it underpins consumer confidence and trade and is vital to innovation. NPL undertake research and shares its expertise with government, business and society to help enhance economic performance and the quality of life.

NPL's measurements help to save lives, protect the environment, enable citizens to feel safe and secure, as well as supporting international trade and companies to innovation. Support in areas such as the development of advanced medical treatments and environmental monitoring helps secure a better quality of life for all.

NPL employs over 500 scientists, based in south west London, in a laboratory, which is amongst the world’s most extensive and sophisticated measurement science buildings.

The National Physical Laboratory is operated on behalf of the National Measurement Office by NPL Management Limited, a wholly owned subsidiary of Serco Group plc. For further information: Switchboard 020 8977 3222 | www.npl.co.uk/contact

### A.1.2 National Institute of Standards and Technology (NIST)

NIST is the equivalent of NPL in the United States of America. Founded in 1901, NIST is a non-regulatory federal agency within the U.S. Department of Commerce. NIST's mission is to promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve quality of life.

The NIST web site at www.nist.gov often contains documents relevant to this guide in Adobe PDF.

### A.1.3 EURAMET

The European Association of National Metrology Institutes (EURAMET) is a Regional Metrology Organisation (RMO) of Europe. It coordinates the cooperation of National Metrology Institutes (NMI) of Europe in fields such as research in metrology, traceability of measurements to the SI units, international recognition of national measurement standards and related Calibration and Measurement Capabilities (CMC) of its members. Through knowledge transfer and cooperation among its members EURAMET facilitates the development of the national metrology infrastructures.

EURAMET serves the promotion of science and research and European co-operation in the field of metrology.

This is realized by the following measures in particular:

- development and support of European-wide research co-operation in the field of metrology and measurement standards;
- development, regular updating and implementation of a European Metrology Research Programme (EMRP);
- support of members and associates when applying for research funds for the purpose of European cooperative projects;
- co-ordination of joint use of special facilities;

- improvement of the efficiency of use of available resources to better meet metrological needs and to assure the traceability of national standards;
- technical co-operation with metrology institutes beyond EURAMET and with other regional and international metrology organisations;
- performing the tasks of a Regional Metrology Organisation (RMO) with the objective of worldwide mutual recognition of national measurement standards and of calibration and measurement certificates;
- promotion and co-ordination of scientific knowledge transfer and experience in the field of metrology;
- representing metrology at the European level and promoting best practice to policy and political decision makers with regard to the metrological infrastructure and European co-operation;
- co-operation with European and international organisations responsible for quality infrastructure, in particular by participation in the preparation of harmonized technical documents.

For more information visit the EURAMET web site at: www.euramet.org

### A.1.4 Institute for Geometrical Product Specification

More information about GPS can be found at the Institute for Geometrical Product Specification website www.ifgps.com. Click on resources for more information on GPS.

## A.2 Networks

### A.2.1 Measurement Network – Engineering and Optical

This special interest group reflects a range of interests from a number of sectors, including advanced manufacturing and engineering, transport and energy. It aims to ensure that the needs of members with an interest in dimensional, mass, temperature and optical measurement are reflected in the range of events held under the Measurement Network. These events provide a forum which enable members to exchange views and information.

For further information visit the website at: www.npl.co.uk/measurement-network/engineering-optical/

### A.2.2 Software Support for Metrology Programme (SSfM)

SSfM is an programme that underpins the NMS, focussing on the use of mathematics and computing in metrology. It aims to achieve a balance between research and development, whilst also extending the range of techniques and applications available to meet the continually changing needs of metrology. The overall aim of the SSfM Programme is to tackle a wide range of generic issues, some of which are problems in metrology that require the application of established software engineering practices, whilst others require advances in mathematics, software engineering or theoretical physics. The programme, thus, includes work in metrology, mathematics, software and theoretical physics, with strong links between the various disciplines.

The SSfM Club is aimed at users and suppliers of metrology software, giving them a say in the direction of the Programme. It is the focal point for the distribution of general information arising from the Programme.

Further details can be found at website: http://www.npl.co.uk/category/384

## A.3 National and International Standards

### A.3.1 British Standards Institution (BSI)

BSI started in 1901 as a committee of engineers determined to standardise the number and type of steel sections in order to make British manufacturers more efficient and competitive. The BSI Group is now the oldest and arguably the most prestigious national standards body in the world and is among the world's leading commodity and product testing organisations. Website www.bsi-group.com.

### A.3.2 International Organisation for Standardization (ISO)

The International Organization for Standardization (ISO) is a worldwide federation of national standards bodies from some 140 countries.

The mission of ISO is to promote the development of standardisation and related activities in the world with a view to facilitating the international exchange of goods and services, and to developing cooperation in the spheres of intellectual, scientific, technological and economic activity.

ISO's work results in international agreements that are published as International Standards.

Further information on ISO can be found at: www.iso.ch

**The following BS and ISO specifications are relevant to this guide.**

ISO 3650 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: 1994 Coordinate Metrology—Part 2: Performance assessment of coordinate measuring machines

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

ISO 10360-3: 2000 Geometrical Product Specifications (GPS) – Acceptance and reverification tests for coordinate measuring machines (CMM)—Part 3: CMMs with the axis of a rotary table as the fourth axis

ISO 10360-4: 2000 Geometrical Product Specifications (GPS) – Acceptance and reverification tests for coordinate measuring machines (CMM)—Part 4: CMMs used is scanning measuring mode

ISO 10360-5: 2010 *Geometrical Product Specifications (GPS) – Acceptance and reverification tests for coordinate measuring machines (CMM)—Part 5: CMMs using multiple-stylus probing systems*

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

BS 7172:1989 British Standard Guide to Assessment of position, size and departure from nominal form of geometric features.

BS 4064/5 Specification for Plain Setting rings For Use With Internal Diameter Measuring Machines

Document VDI/VDE 2617 Accuracy of co-ordinate measuring machines may also be of interest to users of this guide.

## A.4 Traceability

Traceability in measurement is the concept of establishing a valid calibration of a measuring instrument or measurement standard, by a step-by-step comparison with better standards up to an accepted or specified standard. In general, the concept of traceability implies eventual reference to an appropriate national or international standard.

The National Physical Laboratory is the United Kingdom's national standards laboratory. It operates at the heart of the National Measurement System (NMS) which is the infrastructure designed to ensure accuracy and consistency in every physical measurement made in the UK. Chains of traceability link UK companies' measurements directly to national standards held at NPL.

For the majority of industrial applications, companies can establish a link to national measurement standards through the calibration and testing services offered by United Kingdom Accreditation Service (UKAS) accredited laboratories, which are in turn traceable to NPL. However, for challenging or novel measurements to the highest standards of accuracy, which are not catered for by UKAS-accredited laboratories, NPL can often provide a traceable measurement solution directly to industry.

The United Kingdom Accreditation Service is the sole national accreditation body recognised by government to assess, against internationally agreed standards, organisations that provide certification, testing, inspection and calibration services.

Accreditation by UKAS demonstrates the competence, impartiality and performance capability of these evaluators.

UKAS is a non-profit-distributing private company, limited by guarantee. UKAS is independent of Government but is appointed as the national accreditation body by the Accreditation Regulations 2009 (SI No 3155/2009) and operates under a Memorandum of Understanding with the Government through the Secretary of State for Business, Innovation and Skills.

UKAS accreditation demonstrates the integrity and competence of organisations providing calibration, testing, inspection and certification services.

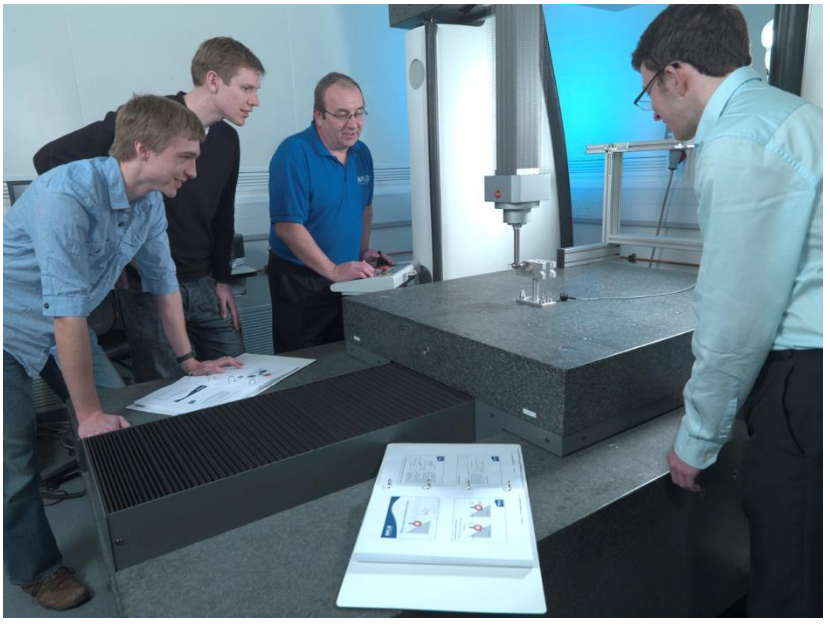
Further information on UKAS can be found at: www.ukas.com.

**The following UKAS laboratories are able to undertake ISO 10360 tests (correct as of July 2011).**

| |
|---|
| 0773 TRAC Measurement Systems Ltd<br>Nedge Hill Science Park, Telford, Shropshire, United Kingdom, TF33AJ<br>+44 (0)1952 2100020 |
| 0827 International Metrology Systems Limited<br>2 Dryden Place, Bilston Glen Industrial Estate, Loanhead, Midlothian, United Kingdom, EH209HP<br>+44 (0)131 440 7525/7508 |
| 0067 Trescal Ltd<br>Park Gate Close, Bredbury Park Way, Bredbury, Stockport, United Kingdom, SK62SL<br>+44 (0) 161 406 7878 |
| 0637 Quality Control Technology Ltd<br>Unit 8 Gainsborough Close, Long Eaton, Nottingham, United Kingdom, NG101PX<br>+44 (0) 115 946 9111 |
| 0605 Status Metrology Solutions Ltd<br>Measurement House, Lenton Street, Sandiacre, Nottingham, United Kingdom, NG105DX<br>+44 (0) 115 939 2228 |
| 0245 Falcon Scientific Instruments<br>The Old Barn, Church End, Raskelf, North Yorkshire, United Kingdom, YO613LG<br>+44 (0)1347 823800 |
| 4057 Interhaze Global Solutions Ltd (trading as) Iso-Tech Calibration Services<br>Unit 3, Riverside Park, East Service Road, Raynesway, Derby, United Kingdom, DE217RW<br>+44 (0)1332 664245 |
| 0333 Eley Metrology Ltd |

| |
|---|
| Beaufort House, Beaufort Court, Mansfield Road, Derby, United Kingdom, DE214FS<br>+44 (0) 1332 367475 |
| 4312 Renishaw plc<br>New Mills, Wotton-under-Edge, Gloucestershire, United Kingdom, GL128JR<br>+44 (0)1453 524524 |
| 0239 Hexagon Metrology Ltd<br>Metrology House, Halesfield 13, Telford, Shropshire, United Kingdom, TF74PL<br>+44 (0)8704 462667 |
| 0199 Avon-Dynamic Calibration<br>Unit 24, Station Road Work Shops, Station Road, Kingswood, Bristol, United Kingdom, BS154PJ<br>+44 (0)117 9701 501 |
| 0332 Mitutoyo (UK) Ltd<br>6 Banner Park, Wickmans Drive, Coventry, United Kingdom, CV49XA<br>+44(0)2476 426 316/317 |
| 0637 Quality Control technology Ltd<br>Unit 8, Gainsborough Close, Long Eaton, Nottingham, United Kingdom, NG101PX<br>+44 (0)115 946 9111 |
| 0762 che coordinate metrology<br>4 Worcester Court, Saxon Business Park, Hanbury Road, Bromsgrove, Worcestershire, United Kingdom, B604FH<br>+44 (0) 1527 558255 |
| 0830 N J Metrology Limited<br>28 Brecon Way, Bedford, United Kingdom, MK418DD<br>+44 (0)800 7318308 |

## A.5 Training courses



### A.5.1 Dimensional measurement Training: Level 1 – Measurement User

A three day training course introducing measurement knowledge focusing upon dimensional techniques.

***Aims & Objectives***

To provide:

- the underpinning knowledge and expertise for anyone who uses measurement tools or requires an appreciation of the importance of measurement,
- the principle knowledge and practical training for people who are required to use dimensional measurement techniques to complete their daily tasks; and
- the tools to instil and encourage questioning culture.

Enabling:

- An understanding of the fundamentals of standards, traceability, calibration, uncertainty, repeatability, drawing symbols and geometrical tolerances, the importance of the relationship between tolerances and measuring equipment and be able to question the measurement.

Level 1 is applicable to all industrial sectors as a stand-alone qualification or as a building block for further NPL Dimensional Measurement Training levels – 2 & 3.

***Course Content***

**Day 1 - Geometric Product Specification (GPS) A**
Including what is GPS, drawing practice and geometrical tolerances.

**Day 2 - Measurement Principles and Methods A**
Including successful measurements, standards, traceability, calibration, uncertainty, units, relationship between tolerances and measuring equipment using micrometers and callipers, repeatability and reproducibility of measurements.

**Day 3 - Measurement Principles and Methods B**
Including the relationship between tolerances and measuring equipment by the use of height gauges, dial test indicators, dial gauges, plug gauges, gap gauges and temperature effects.

NB: Fundamental Measurement Calculation is incorporated into all 3 days including powers, scientific notification and triangles. This is achieved by understanding the relationship of these calculations when applied to tolerance zones and practical measuring tasks.

A workbook of evidence must be completed successfully during the training course and, where required, post assessment tasks can be set for each individual to be completed in the workplace.

### A.5.2 Dimensional Measurement Training: Level 2 - Measurement Applier

A four day training course for those who have a good basic understanding of measurement principles gained through the Level 1 training course.

***Aims & Objectives***

To provide:

- the underpinning knowledge and expertise for anyone who uses measurement tools or requires an appreciation of the importance of measurement,
- the principle knowledge and practical training for people who are required to use co-ordinate measurement techniques to complete their daily tasks; and
- the tools to instil and encourage questioning and planning culture

Enabling:

- a visible return on investment for a manufacturing organisation in the form of various production cost savings and an upskilled workforce,
- a reduction in re-work time and waste on the production line - faults and problems will be detected earlier in the production process; and
- An in-depth appreciation of *why* measurement is carried out and not simply *how*

Level 2 is applicable to all industrial sectors as a stand-alone qualification or as a building block for further NPL Dimensional Measurement Training levels – 3 & 4.

A workbook of evidence must be completed successfully during the training course and, where required, post assessment tasks can be set for each individual to be completed in the workplace.

***Course Content***

**Geometric Product Specification (GPS) B**
Content covered:
GPS standards; Envelope tolerance; Size Principles; ISO Limits and Fits Projected tolerance; Free state condition; Virtual condition; Maximum Material Condition principles; Geometrical tolerancing measurements using first principle measuring equipment; Surface texture principles.

**Measurement Principles and Methods C**
Content covered:
Calibration; Uncertainties; Traceability; Procedures; First Principle

Measurement; Angle plate; Gauge blocks; Surface plate; Height micrometer; Sine bar or sine table.

**Process Control A**
Content covered:
Statistical Process Control theory; Variation – common, special causes; Prevention versus detection; Collecting and calculating data when using measuring tools; Callipers; micrometers; Basic charts – Tally chart/Frequency Table, Histogram, Control Chart; Reacting to variation; Benefits of process control; Standard deviation; Capability indices; Fundamentals of Gauge R&R.

**Measurement Principles and Methods D**
Content covered:
Taper calculations; Angles; Diameters; Searching for triangles; Chords; Radians; Manipulation of formula.

**Co-ordinate Principles A**
Content covered:
***Application of equipment:*** First principles; Co-ordinate Measuring Machine; Optical and vision machines; Articulating arm; Laser tracker; Projector; Microscopes; Height gauge with processor; Contour measurement equipment.
***Machine performance***: Calibration standards; Self-verification/artefacts; Measurement volume.
***Alignment Techniques***: 321/point system alignment; Flat face alignment; Axes alignment; Car line/engine centre line.
***Machine appreciation:*** Ownership; Care; Respect; Cost; Contribution to the business.
***Work Holding:*** Fixturing; Rotary table; Clamping; How to hold the part; Influence of component weight, size, shape; Free state; Restrained state.
***Co-ordinate geometry***: Points; Plane; Line; Circle; Cylinder; Cone; Sphere; Ellipse.
***Sensor Types***: Probing Strategies; Relevant standards; Environment.
***Measurement Strategies:*** Number of points; Partial arc; Contact/non contact.

**Co-ordinate methods A (OEM Training - equipment specific)**
Content covered:
First principles; Co-ordinate Measuring Machine; Optical and vision machines; Articulating arm; Laser tracker; Projector; Microscopes; Height gauge with processor; Contour measurement equipment.

## A.6 Manufacturers

The following is a list of manufacturers providing products or services relevant to this guide. The appearance of a manufacturer in this list is not an endorsement of its products or services. The list contains those companies known to the author and may not be complete.

Kolb & Baumann GmbH & Co. KG
(website: www.koba.de/ index.php?lang=english) are manufacturers of gauge blocks, ball plates (KOBA-check), ball bars and step gauges (KOBA-step). They can be contacted at:

**Kolb & Baumann GmbH & Co. KG**
Fabrik für Präzisions-Messzeuge
Daimlerstraße 24
DE-63741 Aschaffenburg

The UK distributor is OPUS

Mitutoyo make step gauges **(**website: **www.mitutoyo.co.uk).** Mitutoyo's step gauges are referred to by Mitutoyo as 'High Precision Check Master' and 'Standard Check Master.

**Mitutoyo (UK) Ltd**
Heathcote Way
Heathcote Industrial Estate
Warwick
Warwickshire
CV34 6TE

Hexagon Metrology also manufacture step gauges

**Hexagon Metrology (also Tesa and Cary products)**
Metrology House
Halesfield 13
Telford, Shropshire TF7 4PL

Bal-Tec manufacturer ball bars (website: www.bal-tecballs.com)

**Bal-Tec**
1550 E. Slauson Avenue
Los Angeles,
A 90011-5099

Etalon Ag are the manufacturers of the LaserTracer

**ETALON AG**
Premises of the Physikalisch-Technische Bundesanstalt (PTB)
Bundesallee 100
38116 Braunschweig
GERMANY

R**enishaw** are manufacturers of the machine checking gauge and laser interferometer systems

**Renishaw plc**
New Mills
Wotton-under-Edge
Gloucestershire
GL12 8JR
United Kingdom

Saphirwerk Industrieprodukte AG manufacturer of stylus tips and reference and test spheres.

**Saphirwerk Industrieprodukte AG**
Erlenstrasse 36
CH-2555 Brügg
Switzerland

Website: www.saphirwerk.com/english/

# Appendix B ISO 14253 decision rules

Reproduced from NPL Good Practice Guide Number 80.

When making a measurement you may think that it is a simple mater of the result falling within the tolerance band to prove conformance. This is not the case as the following example shows.

The designer has specified that a hole should be 50 mm ± 0.005 mm (top and bottom lines in figure 38). The first operator measures the size with a traceable micrometer as 50.004 mm and states that the hole conforms to the drawing. However, the foreman, looking at this result examines the uncertainty of the micrometer. The measurement uncertainty of the micrometer is 0.003 mm and applying this uncertainty he realises that the actual size could lie between 50.001 mm and 50.007 mm. He gets the hole re-measured on a bore comparator that has a 0.001 mm uncertainty. The measurement comes out at 50.006 mm and conformance is not proven. As a general rule the measurement uncertainty of the equipment should be no greater than ten percent of the tolerance band.

Note that in this case both measurement results agree to within their uncertainties. For measurement 1, however, the measured value is less than the uncertainty away from the upper specification limit (USL) and no real information has been obtained about whether the true value is inside or outside the specification limits.

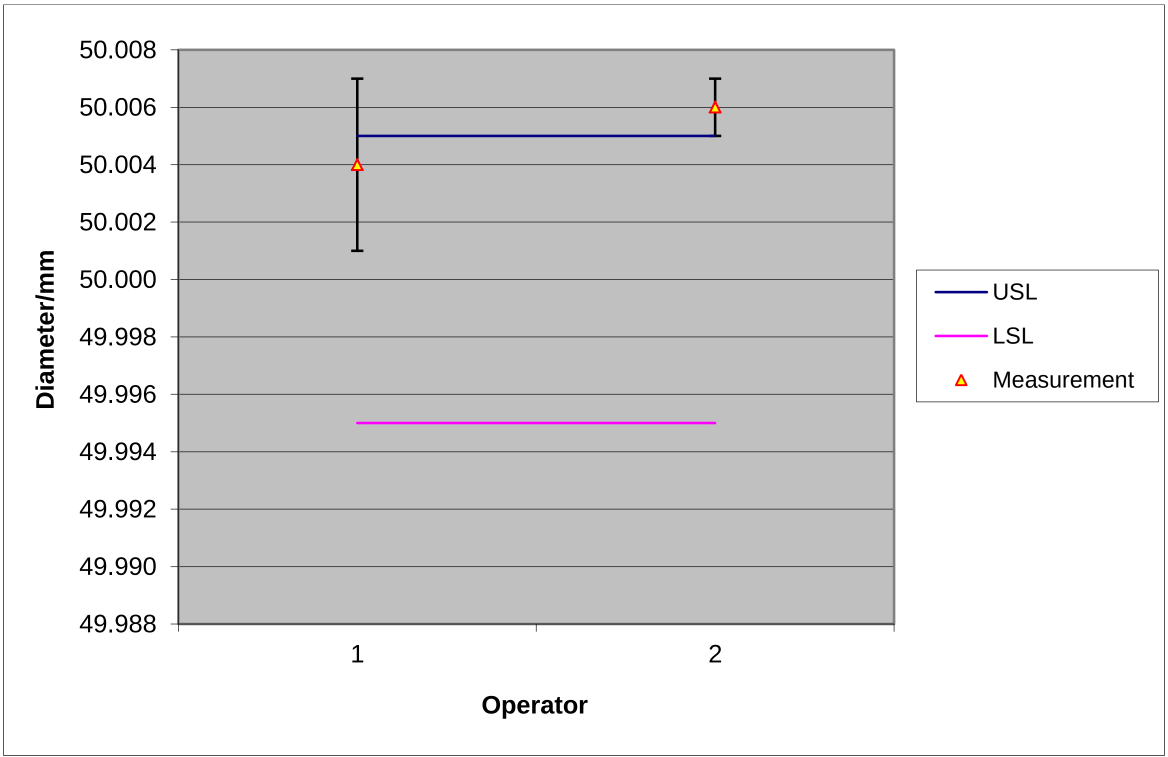


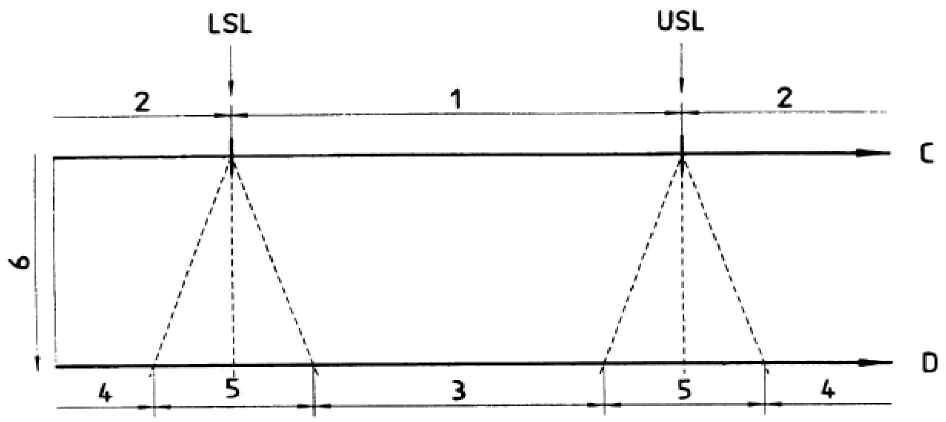

**Figure 38 The two results and their uncertainties**

ISO 14253 recommends that the following rules be applied for the most important specifications controlling the function of the workpiece or the measuring equipment.

At the design stage the terms "in specification" and "out of specification" refer to the areas separated by the upper and lower tolerance (double sided) or either LSL or USL for a one sided specification (see figure 39 areas 1 and 2, line C).

When dealing with the manufacturing or measurement stages of the process the LSL and USL are added to by the measurement uncertainty. The conformance or non-conformance ranges are reduced due by the uncertainty (see Figure 39, line D).

These rules are to be applied when no other rules are in existence between supplier and customer. ISO 14253 allows for other rules to be agreed between customer and supplier. These rules must be fully documented.




Key
C Design/specification phase
D Verification phase
1 Specification zone (in specification)
2 Out of specification
3 Conformance zone
4 Non-conformance zone
5 Uncertainty range
6 Increasing measurement uncertainty, *U*

**Figure 39 Uncertainty of measurement: the uncertainty range reduces the conformance and non-conformance zones (Copyright BSI – extract from BS EN ISO 14253-1:1999)**

Conformance with a specification is proved when the result of measurement, complete statement,[2] falls within the tolerance zone or within the maximum permissible error of the specification for measuring equipment (for example, the maximum permissible error of a CMM). Conformance is also proven when the measurement result falls within the tolerance zone reduced on either side by the expanded uncertainty. The conformance zone is linked to the LSL, USL and actual expanded uncertainty.

[2] A complete statement of the result of a measurement includes information about the uncertainty of measurement.

Non-conformance with a specification is proved when the result of measurement, complete statement, falls outside the tolerance zone or outside the maximum permissible error of the specification for measuring equipment. Non-conformance is also proven when the measurement result is outside the tolerance zone increased on either side by the expanded uncertainty. The non-conformance zone (4 in figure 39) is linked to the USL, LSL and expanded uncertainty.

Neither conformance nor non-conformance with a specification can be proven when the result of measurement, complete statement, includes one of the specification limits (for example, measurement 1 in figure 38 and figure 40).

It is important that the principle behind these rules is applied to a supplier/customer relationship where the uncertainty of measurement always counts against the party who is providing the proof of conformance or non-conformance, *i.e.* the party making the measurement. That is to say the supplier will reduce the tolerance by their measurement uncertainty to prove conformance. The customer will increase the tolerance by their measurement uncertainty to prove non-conformance.

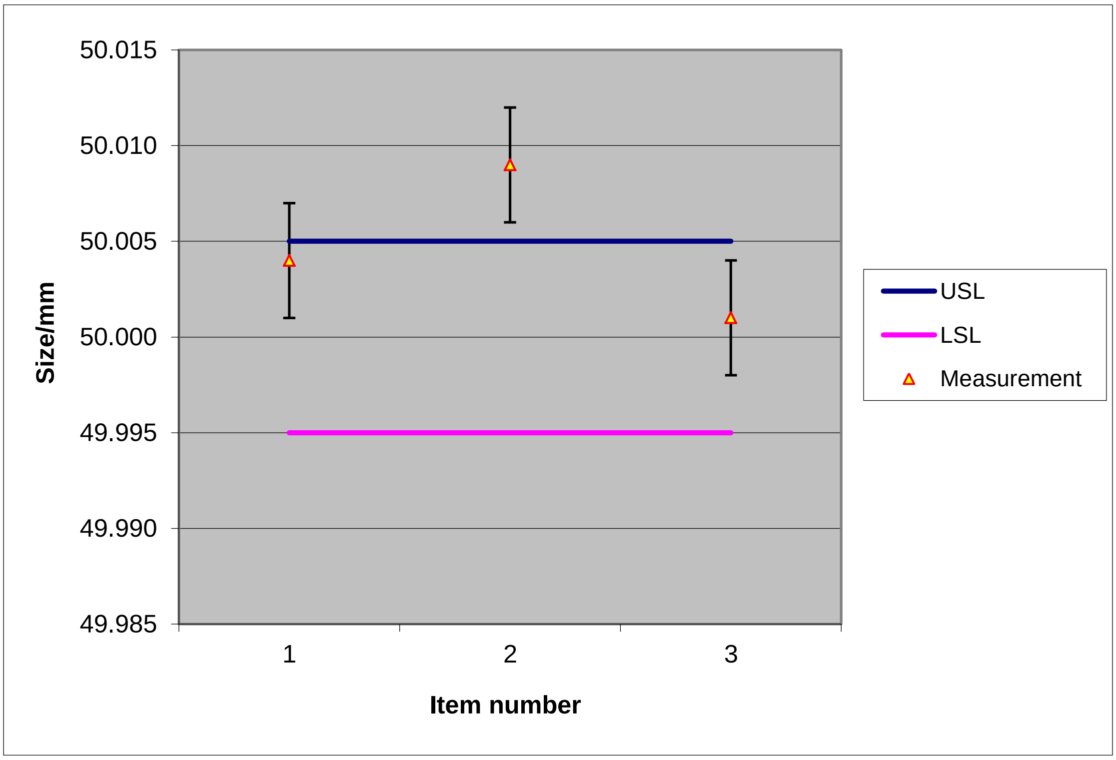



**Figure 40 Conformance or non-conformance**

Referring to figure 40, three items have been measured. The purple line shows the LSL, the blue line the USL.

> Measurement of item 1 - neither conformance nor non-conformance with a specification can be proven.
> Measurement of item 2 – non-conformance is proven.
> Measurement of item 3 – conformance is proven.

In the case of item 1 the result of measurement, complete statement straddles the USL and neither conformance nor non-conformance with a specification can be proven. In the case of item 2 the result of measurement, complete statement is above the USL and so non-conformance is proven. In the case of item 3 the result of measurement, complete statement is above the LSL and below the USL and so conformance is proven.

## B.1 Summary of ISO 14253

ISO 14253 can be summed up in the following statements:

The supplier shall prove conformance in accordance with clause 5.2[3] of BS EN ISO 14253 using their estimated uncertainty of measurement.

The customer shall prove non-conformance in accordance with clause 5.3[4] of BS EN ISO 14253 using their estimated uncertainty of measurement.

When evaluating the measurement result the uncertainty is always at the disadvantage of the party with onus on proof.

In the past the measurement uncertainty has been ignored when ascertaining conformance with a specification as long as the uncertainty was 1/10th of the specification width. This procedure is no longer acceptable.

[3] Rule for proving conformance with specification.
[4] Rule for proving non-conformance with specifications.