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# Coordinate Measuring Machine Calibration

## *PURPOSE*

This document has been produced by EAL to provide information on the measurement capabilities of coordinate measuring machines (CMMs) and the treatment of measured data, and to provide guidance to national accreditation bodies accrediting laboratories to perform task-related calibrations of CMMs, or to use CMMs for the calibration of components.

*Authorship*

This publication has been written by the EAL Expert Group Dimensional Metrology working group on CMMs.

*Official language*

The text may be translated into other languages as required. The English language version remains the definitive version.

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# Contents

# 1 Summary

1.1 The aim of this guideline is to demonstrate the ways in which traceability for measurements using a coordinate measuring machine (CMM) can be achieved.

1.2 Coordinate metrology has become essential for industrial dimensional metrology. In recent years, standards and guidelines have been developed to harmonize the performance specification of a CMM for a user when purchasing a machine and, once purchased, to provide a well-defined way in which the specified performance can be verified.

1.3 A further step in the harmonization process is to establish ways of calibrating components with a CMM, i.e. measuring a component, assessing the uncertainties of the respective measurands, and issuing a certificate, the authenticity of which would be recognised throughout the Western European Calibration Cooperation (WECC). However, due to the complex errors and versatility of a CMM, it is difficult to specify and verify the uncertainty of all measurement tasks that can be executed by a CMM, in any position within its working volume, using any measurement strategy.

1.4 The solution suggested in this guideline is for a laboratory to demonstrate its ability to assess the uncertainty of those measurement tasks for which accreditation is desired. This leads to the concept of task-related calibration, where only those error sources are analysed that affect the particular measurement task and associated measurement procedure specified in the certificate. For some tasks, this will be relatively easy to achieve.

1.5 This guideline describes two basic principles of CMM task-related calibration: the comparator principle and the error synthesis principle. It further summarises the views of experts about the related calibration techniques.

1.6 The functions of this document are to:

- ✷ emphasise the difference between CMM performance verification and CMM calibration,
- ✷ define CMM task-related calibration and to describe the problems involved,
- ✷ provide guidance to the various national accreditation bodies accrediting laboratories to perform task-related calibrations of CMMs and/or to use CMMs for the calibration of components.

# 2 Introduction

2.1 In response to requests from firms and organisations, various national calibration organisations are studying the calibration of Coordinate Measuring Machines (CMMs) and the use of CMMs to calibrate components. Some organisations have issued accreditations for the calibration of components already. In order to harmonize these efforts, a WECC working group was established, which held its first meeting on 4 April 1990 at the PTB, Braunschweig. It was recognized by the working group that existing standards and guidelines, formulated to verify the performance of a CMM according to a strictly defined set of rules, were inadequate if a CMM was to be used to calibrate components. It was agreed that more information on the measurement capabilities of coordinate measuring machines and the treatment of the measured data was required. This guideline is the result of the subsequent meetings and discussions of the group.

# 3 Calibration and performance verification of CMMs

## *3.1 CMM calibration*

3.1.1 According to the *International Vocabulary of Basic and General Terms in Metrology*, a calibration is the assessment of the uncertainties in the final results (measurands) of the measurement task.

Note: Here 'uncertainty' is used as a synonym for 'error'. The uncertainty may contain uncorrected known and unknown systematic effects as well as random effects.

3.1.2 In contrast to simple and single-purpose measuring instruments, CMMs are able to measure a very large family of geometrical parameters. For each of these parameters, there are many possible measurement strategies (eg regarding the number and position of the measured points, or the used probe stylus) that are not standardized. Both the measurement task and the used measurement strategy determine the way errors are introduced in the measurement system and the way they propagate in the hardware and software of the CMM. Since generally there is also no predominant source of error, it is currently not practicable to calibrate a CMM for all the measurement tasks it can handle. The solution is to calibrate a CMM for individual measurement tasks, where both the measurement strategy and measurement conditions are well specified. This is called a task-related calibration.

3.1.3 Based on the concept of task-related calibration, methods and procedures are discussed in the following chapters to establish traceability of measurements performed with a CMM. Furthermore, recommendations are given for the accreditation of calibration laboratories.

## *3.2 CMM performance verification*

3.2.1 Methods to enable a CMM user to specify and verify the performance of a CMM, mainly for the purpose of purchasing a CMM (acceptance testing), have been discussed very actively within the CMM community since the mid-1970s. (The CMM acceptance test, as set out in the appropriate specification standards, provides a mechanism by which a go/no-go decision on the ability of a CMM to perform a series of specific tests can be made. Similar tests are used to periodically check that this level of performance is maintained.) The discussion has resulted in the publication of several national and international standards and guidelines describing the requirements for the performance verification, periodic reverification and interim checking of CMMs. Furthermore, supplementary documents have been prepared to help the CMM user with the interpretation of the requirements of particular specification standards.

3.2.2 Most CMM performance verification standards and guidelines are based on sampling the length-measurement capability of a CMM, to decide whether its performance conforms to the specification. However from such a sample, it is not possible to make an accurate statement about the overall length-measurement capability of a performance-verified CMM. This is due mainly to the complicated ways in which errors combine within a CMM, which do not permit statements about the uncertainty of its measurements anywhere in its workspace to be directly derived from such a limited sample. Furthermore, there are no methods specified by which the uncertainty of other measurands can be calculated using only the length-measurement capability of a CMM.

3.2.3 Thus the sampled length-measurement uncertainty alone cannot be considered as representative of all possible measurement tasks performed by a CMM. Therefore, **performance verification does not guarantee traceability of measurements** performed with a CMM for all measurement tasks.

3.2.4 However, it is recognized by the working group that in an industrial environment the currently practised performance verifications and regular interim checks of CMMs are the state of the art to approximate traceability in case no calibration certificate of the measured components is required.

# 4 Accreditation of calibration laboratories

4.1 The calibration of a mechanical component with a CMM is a complex measurement problem which involves many factors. Each requirement for each geometrical feature, or relationship between features, of the component under test represents a separate measurement task for the CMM. Each measurement task and measurement strategy used to solve it involves a different combination of sources of uncertainties associated with the coordinate measuring system, i.e. the CMM and the environment in which the CMM is sited. Thus a general calibration of CMMs for all the measurement tasks it can handle is not practical. Hence the concept of task-related calibration is introduced where:

- accreditation can be granted only for precisely specified measurement tasks, conditions, and measurement strategies, according to one of the methods described in Section 5,

- only the sources of uncertainty contributing to the final uncertainty associated with the measurement task need to be identified and estimated, and

- ✷ the accreditation bodies are responsible for harmonizing the measurement tasks, including measurement strategies, and the calibration procedures with the requirements of this guideline, especially to analyse systematically the precise nature of the measurement tasks required for the accreditation.

4.2 There are basically two types of technical solutions to accredit the use of CMMs to calibrate components:

- ✷ the use according to the comparator principle, and
- ✷ the use according to the 'error synthesis' technique (sometimes referred to as the parametric technique).

4.3 Regarding the task-related calibration of CMMs according to the error-synthesis technique, additional accreditations are possible for:

- ✷ the measurement of the parametric errors of a CMM, and
- ✷ the evaluation of the uncertainty of a measurement task from the parametric error data of the CMM, according to a specified, task related, procedure. This evaluation may be implemented in software.

4.4 Appendixes B and C give general rules which shall help to setup accreditation contracts for the calibration of CMMs and the use of CMMs to calibrate components.

# 5 Calibration procedures

## *5.1 Comparator approach (see Appendix D)*

5.1.1 The measurement of traceable reference objects yields directly the errors associated with specific measurement tasks. Thus the errors associated with the parameters of the measured object due to the accuracy of the CMM (including its software) can be determined directly. In view of the complex error structure of CMMs, calibrations of this kind are only valid for objects with essentially the same geometrical form and size as the reference object used, measured in the same location and using the same measurement strategy. Provided that suitable reference artefacts are available, this type of calibration procedure can achieve high accuracy with relatively little effort.

5.1.2 Performing a comparator-type calibration is relatively straightforward. The reference object is measured several times by the CMM. Here it is good practice to make small changes in the location of the object and the measurement strategy to establish the sensitivity of the measurements to small differences between the final application of the measurement and such a calibration. In general, no analysis of errors associated with the CMM is required.

5.1.3 Table D1.1 in Appendix D presents a list of requirements for a CMM task-related calibration using the comparator principle. Due to the large variety of measurement tasks which can be performed using a CMM, the list of these requirements has been limited to the more important ones.

5.1.4 As an example of the way this method can be extended to meet practical requirements the following examples are given:

*Example 1*: In the simplest case, a firm or organisation might choose to use a CMM purely as a mechanical comparator. Despite this being a very restrictive use of the capabilities of the CMM, the comparator approach is often an uncomplicated technique to ensure the traceability of measurements.

*Example 2*: In a more complex case, there may be a significant time interval between the measurement of an object and that of the related reference object. In this case the added uncertainty of the measurands due to variations in the environmental conditions (especially temperature) would need to be thoroughly investigated (see Appendix D). This may be done by measuring the reference artifact under typical environmental conditions or by means of uncertainty budgets (eg by analysis of the respective error sources as explained in Section 4.2). In some cases it also may be necessary to verify the stability of the CMM readings in time.

*Example 3*: In a yet more complex case, the objects may need to be measured at different locations in the working volume of the CMM, for example for the measurement of large batches of gauges. In this case, a much more rigorous evaluation of the variation in measurement capability of a CMM with position within its working volume would be necessary in order to check how the geometrical errors of the CMM influence the measured values of the object.

## *5.2 Error synthesis method (parametric approach) (see Appendix E)*

5.2.1 In this section the task-related calibration of CMMs is considered based on an analysis of the errors introduced in the various components of a CMM ( the so-called parametric errors ) and their effect on the errors in the measurand. Although such an analysis is considerably more complex than the comparator approach explained in the preceding section, it can be used to calculate the uncertainty of almost any measurement task without using task-related reference artefacts.

5.2.2 A task-related calibration according to the error synthesis approach usually consists of the following three steps:

(1) Assessment of the CMM's parametric errors. Here only those error sources need to be estimated that are active for the specific measurement task under consideration. Usually this involves the assessment of the geometric and probing errors of the CMM and their response to variations in the environmental conditions as specified in the certificate.

(2) Calculation of the errors in the measured coordinates of each measured point specified in the measurement strategy, as obtained using a particular probing strategy, under specified environmental conditions. These errors are obtained by superposition of the parametric errors.

(3) Combination of the errors in the measured coordinates of the measured points to the errors in the measurands taking into account the estimation software of the CMM.

5.2.3 Step 2 and 3 may be performed by a so-called virtual CMM. A virtual CMM is a model of sufficient complexity to simulate the propagation of the parametric errors to errors in the measurands, as determined by the measurement task and measurement strategy. It enables the simulation of many measurement strategies, eg to determine the best measurement capability.

5.2.4 To illustrate the different levels of complexity of this approach to task related calibration the following examples are given:

*Example 1*: In a simple case, a firm or organisation might want to measure different lengths (eg, the distance between two plain parallel faces of an object), aligned along a particular CMM axis, in a fixed position in the CMM's workspace. In this case only the position error of the respective CMM axis needs to be determined at the positions where the lengths will be measured. The probing errors need only be assessed for one axis direction.

*Example 2*: In a more complex case, the length measurements are to be made in different positions in the CMM's workspace. In this case also the pitch and yaw errors of the CMM axis along which the object is aligned need to be considered.

*Example 3*: In a yet more complex case, measurements are to be made for lengths in various orientations. In this case the geometric errors of all CMM axes need to be considered as well as probing errors in various directions.

*Example 4*: A length can be a distance between two points that are not measured but defined as the intersection of measured geometrical elements (eg, as the intersection of a cylinder axis with a plane). In this case the introduction and propagation of errors by the CMM software has to be considered in more detail.

5.2.5 These examples illustrate that the error sources to be addressed in a task related calibration are affected by the chosen measurement strategy. Often a significant reduction of the required calibration effort can be achieved by choosing a suitable measurement strategy. Especially reversal or 'swing-round' methods are powerful techniques to reduce or eliminate the effects of certain error sources and thus simplify the respective task-related calibration.

## *5.3 Hybrid approach*

5.3.1 There may be applications where a combination of the comparator method and the parametric method are appropriate.:

*Example 1*: As an example of the hybrid approach we consider the calibration of a cylinder aligned with the Z-axis of a CMM. Here a ring gauge is used to establish traceability of the roundness and diameter of a cross-section (ie using a comparator approach). A complete calibration of the cylinder can be achieved if also the straightness of the Z-movement and the pitch errors of the X- and Y-movements are known.

## *5.4 Choice of appropriate approach*

5.4.1 Calibration using the comparator approach is a simple yet reliable and accurate technique. The comparator approach is recommended for all those measurements where calibrated reference artefacts are available economically. The error synthesis approach enables the user to assess the different calibration tasks using the same primary error data. It is recommended for all those cases where no comparator approach is possible due to financial or logistic problems. It is a particularly versatile approach.

5.4.2 Further criteria for the method to be adopted are:

- the overall cost of the calibration procedure;
- availability of error analysis software;
- availability of task-related reference artifacts;
- availability of artifacts or measurement equipment to assess parametric errors;
- the speed of the calibration procedure;
- the size of the CMMs covered by the technique;
- the frequency of use of the CMM;
- the accuracy of the method; and,
- the spectrum of calibration tasks to be performed on the CMM.

# 6 Calibration certificates

6.1 It is recommended that, in the first instance, advice is sought from accreditation bodies already involved with issuing certificates for CMM task-related calibration.

# 7 Future

7.1 The task-related calibration of CMMs is a relatively new field. A brief survey of recommended research projects is presented in Appendix F.

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# Appendix A

## *Terms and definitions*

Terms defined in the VIM (International Vocabulary of Basic and General Terms in Metrology) and ISO 10360 Parts 1 and 2 are adopted, where possible.

A.1 **Coordinate measuring machine (CMM)** A measuring system, fixed in place during use, designed to take measurements from at least two linear and/ or angular displacements generated by the CMM. At least one of the displacements shall be a linear measurement.

A.2 **Indication of a CMM** The value of a measurand provided by the CMM.

*Note 1*: In general a CMM is equipped with a computer and associated software to estimate geometrical properties from the measured coordinates of a set of points. In these cases both computer and software are considered part of the CMM and the estimated geometrical properties constitute its indication.

*Note 2*: Examples of measurands are diameter, length and squareness.

A.3 **Error of indication of a CMM** The indication of a CMM minus the (conventional) true value of the measurand.

*Note*: The (conventional) true value is dependent on related definitions in national and international standards.

A.4 **Task-related calibration of a CMM** 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.

*Note 1*: The result of a task-related calibration is recorded in a document, called a calibration certificate.

*Note 2*: The result of a task-related CMM calibration permits the estimation of errors of indication of the CMM for the limited family of precisely defined measurement tasks specified in the calibration certificate.

*Note 3*: The result of a task-related calibration is limited to the precisely defined measurement strategy(s) (eg, the number and position of the measured points) used to solve the measurement task(s) and specified in the certificate.

A.6 **Performance verification of a CMM (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.

*Note 1*: Performance verification does not ensure traceability.

*Note 2*: There are various national and international guidelines and standards which describe these operations.

A.7 **Inspection of a CMM (interim check)** Set of operations specified by the user to test the accuracy of a CMM.

*Note 1*: Usually performed in regular intervals in order to increase the level of confidence in the measurements taken with a CMM.

*Note 2*: There exist various national and international guidelines and standards which describe these tests.

A.8 **Accreditation** The formal recognition that a calibration laboratory is competent to carry out specific calibrations.

*Note 1*: EN 45001, EN 45002 and various WECC interpretation documents are available which describe the requirements needed to obtain an accreditation.

A.9 **Best measurement capability** The smallest uncertainty of measurement for a certain measurement quantity within a specified range, assigned to an accredited laboratory.

*Note 1*: The best measurement capability is determined either by assessing a budget of contributing uncertainty components and/or by means of an inter-laboratory comparison.

*Note 2*: The best measurement capability of a laboratory shall be determined over specified ranges for each quantity for which accreditation is granted.

A.10 **Virtual CMM** A procedure which predicts the errors of indication of the CMM for a number of tasks by creating a mathematical model for the introduction and propagation of errors in the CMM components and CMM software.

A.11 **Geometric errors** The departures from the ideal geometry caused by a lack of mechanical perfection in the moving elements of the CMM.

*Note 1*: 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.

A.12 **Probing errors** Dominating errors in the measurands of small artifacts. Usually a calibrated sphere of 20 mm to 30 mm is used to assess the probing errors: The apparent form error is usually interpreted as the probing error.

A.13 **Probe errors** The errors in the measurement of coordinates associated with the probe measuring system.

*Note 1*: In general it is both not possible nor required to completely isolate probe errors from probing errors.

A.14 **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.

A.15 **Parametric error analysis** A method by which individual errors associated with specific CMM components (usually geometric and probing errors) are determined and then combined, using a mathematical model corresponding to the kinematic configuration of the CMM, to calculate the errors of the measurement task.

*Note*: In general only a limited number of error sources need to be considered.

# Appendix B

## *Accreditation of laboratories for the calibration of CMMs*

The following general rules are to be observed:

- Accreditation is granted for particular CMM types;
- Accreditation is granted for a specified size of the calibrated volume;
- Accreditation is granted for a specified set of measurement tasks;
- Accreditation is granted for specified environmental conditions;
- The method employed in the calibration procedure must be documented;
- The claimed uncertainty must be specified by an uncertainty budget;
- Accreditation requires auditing and regular intercomparisons;
- The software packages used must be specified;
- The calibration laboratory must have the appropriate calibration standards traceable to the national standards laboratories;

# Appendix C

## *Accreditation of laboratories for calibration of artefacts using CMMs*

The following general rules are to be observed:

- Accreditation is granted for one particular CMM;
- Accreditation is granted for a specified measurement task;
- Accreditation is granted for a specified measurement strategy;
- Accreditation is granted for specified environmental conditions;
- After calibration the CMM may not be changed in location and constellation;
- The method employed in the calibration procedure must be documented;
- The claimed uncertainty must be specified by an uncertainty budget;
- Accreditation requires auditing and regular intercomparisons;
- The calibration laboratory using the CMM is responsible to maintain the validity of its calibration by interim checks;
- The calibration laboratory using the CMM is responsible to maintain the environmental conditions corresponding to those conditions used for the uncertainty budget.

# Appendix D

## *Comparator approach*

D1.1 Table D1.1 presents a list of requirements for a CMM task-related calibration using the comparator principle. Due to the large variety of measurement tasks which can be performed using a CMM, the list of these requirements has been limited to the more important ones.

**Table D1.1 Requirements for CMM task-related calibration using the comparator principle**

| Parameter | Maximum variation |
|---|---|
| Geometric features | 10% difference in lengths, angles, etc. Larger differences need experimental verification according to the judgement of the accreditation body |
| Accuracy of the geometrical feature | 50% deviation from the mathematically ideal geometry (roundness, flatness, etc.) referred to the required uncertainty of calibration |
| Calibration of the reference object | As required by the uncertainty budget |
| Equivalence of non-geometric properties (eg elasticity, hardness, surface texture, mass) | 'Sufficiently equal' to the application |
| Equivalence of measurement strategy and conditions | |
| • Object position | 10% of the relevant dimensions of the object or 25 mm, whichever is the greater* |
| • Object orientation | 5° * |
| • Offset of measured points | Dependent on the 'wavelength' of the ideal surface |
| • Measuring force | 20% * |
| • Probe configuration | 10% of stylus length* |
| • Sequence of measured points | Same points and measurement task |
| • Environmental conditions | Assessment by uncertainty budget or experimentally |
| Maximum elapsed time between calibration and application | Dependent on the task and environmental conditions* |

* These values shall be experimentally verified for each task stated in the accreditation by experiments on the CMM to be used, and if necessary, corrected according to the judgment of the accreditation body.

D1.2 The environmental conditions, in particular temperature, have a significant influence on the error sources of a CMM. The thermal conditions during the measurement of the reference artefact are to be recorded. These conditions are defined as the reference conditions. It is assumed that each deviation from the reference conditions adds to the measurement uncertainty of the CMM. Limits concerning the difference between the reference conditions and the actual conditions during the measurements shall be stated in the calibration certificate. These limits can be assessed by means of uncertainty budgets or experiments (eg, by re-measuring the reference artefacts under typical environmental conditions). The user of a CMM is responsible to guarantee the operation of the CMM within the stated limits. Generally it is recommended to measure the reference artefact before and after the object(s) to be calibrated.

# Appendix E

## *Error synthesis approach*

### E1 Assessment of the CMM's parametric errors

E1.1 Spatial errors are errors in the measured position of a point on the surface of the workpiece as obtained using a particular probing strategy, under specified environmental conditions. These errors are influenced by:

- ✳ the lack of perfection associated with the hardware components of the CMM, for example the CMM guideways, the angular- and linear-displacement-measuring system and the characteristics of the probe system;
- ✳ the environment within which the CMM is sited, for example the ambient temperature, temperature gradients (both in time and space), humidity and vibrations;
- ✳ the probing strategy, which encompasses such factors as: the magnitude and direction of the probe measuring force, the type of probe stylus and sphere used, and the measuring speed of the probe;
- ✳ the reference artefacts to qualify the probe;
- ✳ the workpiece characteristics, for example the elasticity, surface roughness, hardness and mass.

E1.2 There is no ready-to-use reference with which the errors of all positions of a 3D measuring instrument can be directly determined in all the six degrees of freedom in each position of the CMM's workspace (orientation errors have to be determined in order to analyse Abbé errors due to the various possible configurations of the probe styli). This is why for the present one can do nothing else except measure all the individual errors associated with each of the axes of a CMM and the probe system. These errors are called parametric errors and are combined analytically to calculate the errors in the measured coordinates of each measured point. The type of equations involved in such a computation can be found in the technical literature.

E1.3 In general, for each CMM axis there are six parametric errors to be measured as function of the axis position. Furthermore, a squareness error must be determined for each pair of axes, yielding an overall total of 21 parametric errors for a CMM with three linear axes. The techniques currently used to determine the parametric errors can be divided into two groups:

- ✳ **direct measurements** which use conventional measuring equipment and artefacts, such as a laser interferometer, electronic levels, a straight edge and a square to individually measure each parametric error;
- ✳ **indirect measurements** which use the differences between the indicated values and the calibrated values of features on reference artefacts, such as ring gauges, holeplates, space frames and step gauges in a multiplicity of locations throughout the complete work space of the CMM. From these differences the CMM's parametric errors can be estimated. Also uncalibrated artifacts can be used for this purpose, in which case the variations in the measurands obtained in different artifact locations are used in the

estimation. At least one calibrated length should be measured in case all parametric errors are to be assessed.

E1.5 Direct measurement of the parametric errors of a CMM provides comprehensive information with a very high sampling density, but this approach requires considerable time, skill and expensive equipment. In contrast, the indirect measurements can usually be performed by the normal CMM operator. It has to be noted that part of the parametric errors can be corrected numerically in the result of a measurement. The direct measurement of parametric errors on a numerically corrected CMM may not show these errors as they are effective in the final measurement result.

E1.6 Table E1.1 gives a summary of the methods that are usually used for the direct measurement of parametric errors associated with a CMM. More information is available in VDI 2617 Part 3 or NKO PR 4.2.

**Table E1.1 Frequently used equipment to measure the parametric errors of a CMM**

| Errors | Measurement equipment or standard |
|---|---|
| *Linear axis* | |
| Positional errors | Laser interferometer<br>Step gauge<br>End gauges |
| Straightness errors | Straightness interferometer<br>Straight edge<br>Alignment telescope with target<br>Alignment laser |
| Pitch and yaw errors | Differential interferometer<br>Electronic levels<br>Autocollimator<br>Measurement positional error along lines with small and large Abbé offset |
| Roll errors | Electronic levels (only for horizontal axes)<br>Reference flat<br>Straight edge whose parallel displacement is monitored |
| Squareness errors between axis | Optical straightness measuring instrument and pentagon prism<br>Mechanical squareness standard<br>Length standards inclined under defined angles |
| *Axis of rotation* | |
| Angular position<br>Precision polygons | Rotary encoders |
| Camming | Test cylinders, flatness standards |
| Axial error | Test spheres, flatness standards |
| Run out | Test cylinders, test spheres |
| *Probing* | Reference sphere<br>Reference ring<br>End gauge |

E1.7 In order to avoid misinterpretation of the translational error components due to Abbe effects, the positional, squareness and straightness errors must be presented along specified lines in the workspace of the CMM. This can be achieved by measuring these errors along those lines or by correcting the translational errors for the Abbé effect by the measured rotational errors.

E1.8 It is recommended that the probing error is assessed for each probe configuration used to carry out measurements with the calibrated CMM. Each probe tip is set up and qualified using the same procedure as when performing measurements with the CMM. The probing error is determined by the measurement of at least 40 points on a calibrated reference sphere, in a nearly uniform distribution over a full hemisphere.

E1.9 For some task related calibrations, the evaluation of the probing system might be limited to its 1D or 2D errors. In those cases, the probing errors can be determined using end standards, for example gauge blocks, and the reference sphere mentioned.

E1.10 In the calibration certificate, the measured parametric errors as well as all other results have to be stated with their uncertainties. These uncertainties are related to the repeatability of the CMM, the uncertainty of the calibration equipment used, the sampling density, the effect of thermal errors and the effects of the finite stiffness of components, which has an important influence on the validity of the rigid body model.

## E2 Calculation of the errors in the measured position of a point

E2.1 In this section the parametric errors are combined to calculate the errors of the measured points. Two techniques or a combination of both can be used:

- ✷ **Numerical simulation**: the parametric errors at the studied position of the CMM axes are calculated by interpolation or regression of the corresponding measurement data. The errors in the measured coordinates of the probe-tip of the CMM are then calculated as the sum of the various translational errors and angular errors, the latter multiplied with the appropriate Abbé offsets.

- ✷ **Statistical analysis**: the parametric errors of a CMM are treated as random variables. In accordance with the WECC document 19 (EAL-G1), the uncertainty of the measured coordinates is calculated from a) the statistical description of the measurement data used to derive the parametric errors and, b) a model for their effect on the computed coordinates.

## E3 Assessment of the errors in the measured feature

E3.1 One of the most important tasks for the CMM software is to determine the workpiece geometry from a set of measured point coordinates. This process introduces and transforms the errors in the measured point coordinates to errors in the estimated features. In the calibration of a CMM, two effects of this transformation have to be considered:

- the (mathematically pure) propagation of errors. This results in errors in the estimated feature that can be explained fully by the errors in the measured coordinates of the points in association with the properties of the estimation principle used (for example, the Gaussian or Chebyshev methods),
- the introduction of errors due to the limited accuracy of the software-computer combination of the CMM. This yields errors in the estimated geometry of the workpiece that cannot be explained by the mathematically pure propagation of errors.

E3.2 The following approach is suggested (although other approaches may be possible) to calculate the task-related errors of a CMM, including the above effects.

- The CMM software is tested for example using data-sets for which a proven solution is available. These tests should guarantee that the errors introduced by the respective software and computer can be neglected compared to the errors introduced by the CMM. Data sets of this kind are available for some estimation tasks (especially to test the estimation of geometrical primitives). It is worth noting that these tests have to be performed only once for each revision of the software. The errors in the estimated workpiece's geometry can now be evaluated by comparing the geometry estimated with:

  (a) the nominal point coordinates and

  (b) the nominal coordinates plus the appropriate error vectors of the probing points.

  The uncertainty of the result can be evaluated using Monte Carlo techniques to model the variation of the error vector of the measured coordinates.

E3.3 Using this approach it is possible to determine the accuracy of a certain measurement task. Other measurement tasks can be evaluated, usually with the same parametric error data. Using appropriate software (eg a virtual CMM), this simulation can usually be performed by a computer. Thus it is possible to extend the application area of the calibration as described in Section 4, by simulating many measurement tasks. A typical example of this approach is the 'brute force' evaluation of the length-measurement capability of a CMM, by calculating the accuracy of many (say, 10 000) length measurements simulated throughout various locations in the workspace of a CMM.

## E4 Special problems of CMM calibrations

### *E4.1 Temperature distribution of the CMM*

E4.1.1 The environmental conditions associated with CMMs, in particular temperature, significantly influence the sources of errors of a CMM.

E4.1.2 It is strongly recommended that the thermal conditions (average environmental temperature and spatial gradients) are recorded during the calibration procedure. These conditions are defined as the reference conditions, ie the conditions to which the calibration is referred.

E4.1.3 It is assumed that each departure from these reference conditions adds to the measurement uncertainty of the CMM. Hence additional margins in the uncertainty budget for each measurement task must be expected, allowing the temperature distribution in the CMM and in its environment to vary within certain limits, and allowing for certain errors in the CMM's own temperature measuring system (if applicable). The user of the CMM is responsible to keep the temperature distribution inside the stated limits.

*E4.2 Redundant axes*

E4.2.1 Many CMMs have more than 3 linear axes, for example a rotary table, a CNC-controlled probe head, or a dual arm configuration.

E4.2.2 Purely comparator-type calibrations do not need error models of the CMM, and hence their application to component measurement is straightforward even for CMMs with redundant axes.

E4.2.3 Any simulation requires precise specification of the axes positions used to realize the probe position, because a single point may be reached in an infinity of ways by a combination of redundant axes.. This can be illustrated by the example of a CMM that has a high-accuracy rotary table, and a Cartesian system with large systematic errors but with good reproducibility. This measuring system can achieve excellent results as well as very poor results, depending upon the measurement strategy employed.

*E4.3 CMMs with non-rigid-body behaviour*

E4.3.1 Not all mathematical models nor all assessment techniques can determine the influence of the errors associated with the axes of motion which depend on the position of other axes. This typically is the case with horizontal arm CMMs. Comparator-type calibrations automatically include these effects.

*E4.4 Stability*

E4.4.1 A CMM's parametric errors can change in time (eg due to collisions or wear). This requires methods for the quick, easy and hence frequently performed assessment of the CMM stability. This assessment is the responsibility of the CMM user.

E4.4.2 1D, 2D and 3D artefacts are well suited to assess CMM stability. As only changes in parametric errors have to be detected, a few datum points along each CMM axis are sufficient to assess the stability of the CMM. The first stability assessment should be performed immediately after the calibration. Subsequent reassessments are compared with this result. A new calibration is required if the observed changes exceed those changes taken into account in the uncertainty budget.

*E4.5 Large CMMs*

E4.5.1 Large CMMs pose several additional problems including:

- ✳ the use of large artefacts is a problem because of their availability, the difficulties associated with their handling, temperature problems and the extended time needed for measurements.

✷ changes in the foundations can limit the stability of large machines. These effects are to a significant extent dependent upon the installation of a specific CMM and are therefore difficult to predict and hence to model. Any calibration of a large CMM should therefore include long term studies of its stability (see Section E4.4).

*E4.6 CMMs with numerical error correction*

E4.6.1 Not all parametric errors of CMMs with numerical error correction can be assessed by direct measurement methods, such as laser interferometry, level meters or autocollimators. The reason is that the correction is applied to the measured data rather than to the geometrical form of the carriages of the CMMs. Hence the effect of an often unknown part of the measured parametric error may be corrected in the software or controller of the CMM. For this reason one usually has to use measurements on artefacts to extract the uncorrected, and hence effective, part of the parametric errors.

## E5 Example - the PTB method of determining parametric errors from measurements on 2D reference artefacts

E5.1 The method serves to determine the 21 parametric errors of a CMM or other machine with 3 linear axes which can be described by a rigid-body model. A calibrated ballplate or holeplate is used, which should have reference elements (balls or cylinder bores) arranged in an equidistant raster. The procedure is to measure the plate in 4 different positions in the working space. These positions represent 3 cross sections of the working space. The direction normal to the surface of the plate in each of the cross sections is parallel to a different machine axis (see Figure E5.1).

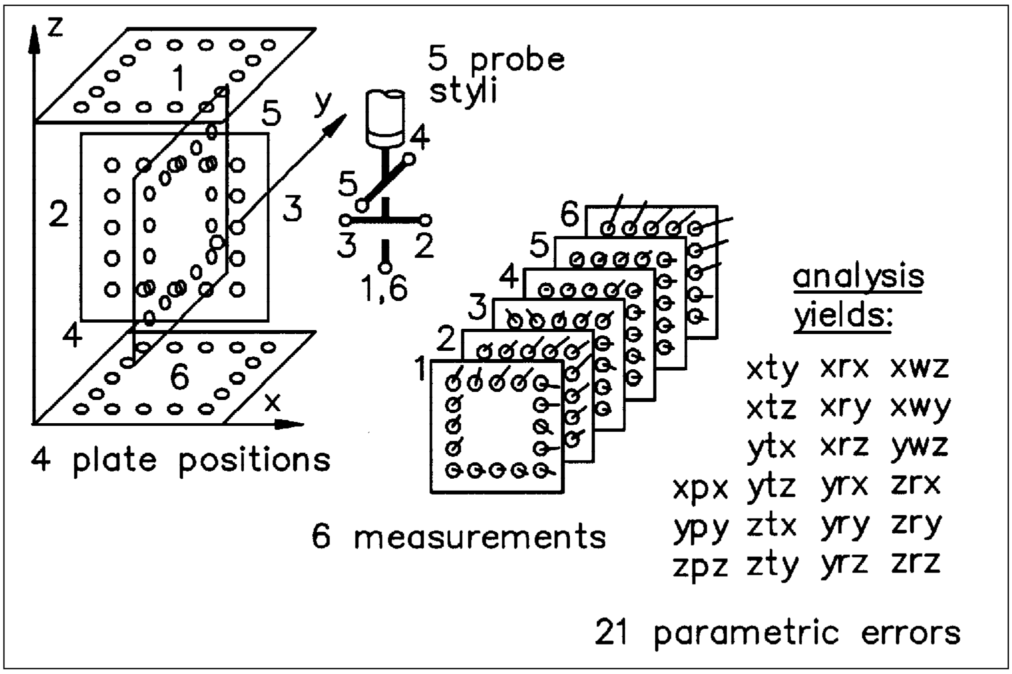


**Figure E5.1 The measurement procedure for assessing the 21 parametric errors of a CMM using a hole-plate**

E5.2 With the plate parallel to each coordinate plane, 2 measurements are performed so that different effective distances from the coordinate axes are obtained, either by shifting the plate (parallel to itself) or by using 2 different probe styli. This results in 2 parallel positions which are normal to the third kinematic axis (ram), and two further positions, one where the plate is parallel to the first, and one where it is parallel to the second kinematic axis.

E5.3 From the 6 sets of measurements the 18 error functions, corresponding to the 3 times 6 degrees of freedom of three axes of motion, are determined by a fitting algorithm. The density of data points obtained is the same as the raster spacing on the plate. The 3 squareness errors are also estimated.

The accuracy of the method is determined by the:

- calibration uncertainty of the plate, which is currently 0.7 µm for a 0.5 $m^2$ plate,
- stability of the CMM,
- reproducibility of the CMM,
- validity of the rigid body model for the CMM.

# Appendix F

## *Recommendations for future developments*

### F1 Intercomparison of methods to assess the error components of CMMs

F1.1 The availability of easy to handle and not costly methods is an indispensable prerequisite for the successful implementation of calibration methods. The intercomparison shall compare existing 'state-of-the-art' as well as 'proven' methods. All interested European laboratories should be invited for this intercomparison.

### F2 Study about artefacts suited for the assessment of the error components of CMM

F2.1 It is often very difficult to judge the qualities of mechanical reference artefacts because there are so many different and often conflicting requirements, for example:

- ✶ price;
- ✶ handling (ease, speed);
- ✶ potential accuracy of their calibration;
- ✶ calibration cost;
- ✶ suitability for other, lower level, CMM-checks to minimise investment;
- ✶ the amount of information about the CMM-errors obtained per probed point;
- ✶ mechanical long-term stability; and
- ✶ thermomechanical behaviour.

F2.2 An intercomparison of suitable artefacts is suggested. This shall serve three purposes:

- ✶ the improvement of the laboratories' capability for the calibration of the artefacts,
- ✶ to gain practical experience about the stability of the artefacts,
- ✶ the standardization of artefacts.

## F3 Development of methods for the assessment of task-related errors

F3.1 An international cooperation project on the development of methods for task-related error analysis is recommended. This project shall fulfil the following tasks:

- ✳ study the possibility of an *a priori* error analysis, i.e. the analysis of task-related errors to be expected during a measurement. This analysis shall be done when defining the measurement task.
- ✳ study the possibility of an error analysis which is integrated in the CMM's computer and cooperates with the CMM's evaluation software. Thus the uncertainties of the executed measurement tasks are automatically assessed.

## F4 Data bank of CMM errors

F4.1 A data bank with the errors of CMMs studied by the collaborating laboratories shall be set up. This will have the advantage that:

- ✳ results can be compared;
- ✳ a statistically meaningful number of CMM error sets are available to test the error assessment methods on real data;
- ✳ information on errors and stability of a large number of CMMs will become available;
- ✳ the handling of the data bank will stimulate the exchange of experience between laboratories.

## F5 Development of methods for the assessment and modelling of probing errors

## F6 Development of methods for the assessment and modelling of rotary table errors

## F7 Development of methods for the assessment and modelling of the elastic behaviour of CMMs