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End-face image analysis procedure for the calibration of optical fibre geometry test sets

Táto norma obsahuje anglickú verziu európskej normy.
This standard includes the English version of the European Standard.

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EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

EN 61745

October 2017

ICS 33.180.01

English Version

End-face image analysis procedure for the calibration of optical fibre geometry test sets (IEC 61745:2017)

Procédure d'analyse d'image d'extrémité pour l'étalonnage de dispositifs d'essais de géométrie des fibres optiques
(IEC 61745:2017)

Endflächen-Bildanalyseverfahren für die Kalibrierung von Prüfeinrichtungen für die Geometrie von Lichtwellenleitern
(IEC 61745:2017)

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European foreword

The text of document 86/510/CDV, future edition 2 of IEC 61745, prepared by IEC/TC 86 "Fibre optics" was submitted to the IEC-CENELEC parallel vote and approved by CENELEC as EN 61745:2017.

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IEC 61745

Edition 2.0 2017-07

INTERNATIONAL STANDARD

NORME INTERNATIONALE

End-face image analysis procedure for the calibration of optical fibre geometry test sets

Procédure d'analyse d'image d'extrémité pour l'étalonnage de dispositifs d'essais de géométrie des fibres optiques

IEC 61745:2017-07(en-fr)

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INTERNATIONAL STANDARD

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Procédure d'analyse d'image d’extrémité pour l'étalonnage de dispositifs d'essais de géométrie des fibres optiques

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

COMMISSION
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END-FACE IMAGE ANALYSIS PROCEDURE FOR THE CALIBRATION OF OPTICAL FIBRE GEOMETRY TEST SETS

FOREWORD

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International Standard IEC 61745 has been prepared by IEC technical committee 86: Fibre optics.

This second edition cancels and replaces the first edition, published in 1998, and constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) removal of the limitation of single mode optical fibre geometry test sets to include multimode;
b) addition of a new annex as mathematical basis.

The text of this International Standard is based on the following documents:

CDV	Report on voting
86/510/CDV	86/516/RVC

Full information on the voting for the approval of this International Standard can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

INTRODUCTION

In the research and production environments, there exists a range of test methods for characterizing the geometry of optical fibres. Furthermore, each test method may determine one or more of the many parameters required for complete geometrical characterization. IEC 61745 describes the calibration of test sets that perform end-face image analysis, also known as "near-field" or "grey-scale" analysis. The principles, however, may be applied to test sets of a different type.

END-FACE IMAGE ANALYSIS PROCEDURE FOR THE CALIBRATION OF OPTICAL FIBRE GEOMETRY TEST SETS

1 Scope

This document describes the calibration of test sets that perform end-face image analysis, also known as "near-field" or "grey-scale" analysis. The principles, however, can be applied to test sets of a different type.

The procedures outlined are performed by calibration laboratories and by the manufacturers or users of geometry test sets, for the purpose of calibrating geometry test sets and for evaluating the uncertainties in measurements made on calibrated test sets. The calibration of fibre coating or cable measurement test sets is not covered by this document.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purpose of this International Standard, the following definitions apply.

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

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

3.1
accredited calibration laboratory
calibration laboratory authorized by an appropriate national organization to issue calibration certificates that demonstrates traceability to national standards

3.2
artefact
object that is measured on or used to calibrate a geometry test set

EXAMPLE An optical fibre and a chromium-on-glass pattern are examples of artefacts.

3.3
calibration
set of operations that establish, under specified conditions, the relationship between the values of quantities indicated by a measuring instrument and the corresponding values realized by standards

Note 1 to entry: The results of a calibration permit either the assignment of measurand values to the indications or the determination of corrections with respect to the indications.

Note 2 to entry: A calibration may also determine other metrological properties such as the effects of influence quantities.

Note 3 to entry: The result of a calibration may be recorded in a document, called a "calibration certificate" or a "calibration report".

3.4
calibration chain
chain of transfers from a national standard to the geometry test set through intermediate or working standards

Note 1 to entry: See $U = k \times u$.

3.5
calibration checking
establishing that a geometry test set that has been previously calibrated but has reached its calibration due date remains within specified uncertainty limits

Note 1 to entry: If the geometry test set has drifted outside these limits, then re-calibration is required. Otherwise, the re-checking period can be extended for a stated period.

Note 2 to entry: The test set may be checked using a working standard.

3.6
calibration standard
artefact that is calibrated against a reference standard and is used to calibrate test sets

Note 1 to entry: The artefact may be a fibre or a chromium-on-glass pattern.

Note 2 to entry: Proper use of a calibration standard ensures traceability.

Note 3 to entry: The term includes the reference standard, the transfer standard and the working standard(s), in descending order of metrological uncertainty.

3.7
combined standard uncertainty
combination of a number of individual standard uncertainties

Note 1 to entry: The term "accuracy" should be avoided in this context.

Note 2 to entry: In calibration reports and technical data sheets, the combined standard uncertainty in the geometry test set measurement is reported as an overall expanded uncertainty with the applicable confidence level, for example 95,5% or 99,7 %.

3.8
confidence level
estimation of the probability that the true value of a measured parameter lies within a given range (expanded uncertainty)

3.9
correction offset
number that is added to or subtracted from the measurement result of a test set to correct for a known physical effect

3.10
coverage factor
k
factor used to calculate the expanded uncertainty, U, from the standard uncertainty, u

3.11
expanded uncertainty
U
range of values within which the measurement parameter, at the stated confidence level, can be expected to lie

Note 1 to entry: It is equal to the coverage factor, k, times the combined standard uncertainty u

$$U = k \times u \tag{1}$$

Note 2 to entry: When the distribution of uncertainties is assumed to be normal and a large number of measurements are made, then confidence levels of 68,3 %, 95,5 % and 99,7 % correspond to k values of 1, 2 and 3 respectively.

3.12
geometry test set
instrument used to measure the geometrical parameters of an optical fibre

Note 1 to entry: The parameters measured will depend on the type of geometry test set.

3.13
infant fibre
fibre whose geometry is to be measured on a calibrated geometry test set

3.14
instrument state
description of the measurement conditions of the geometry test set during calibration and measurement

Note 1 to entry: The measurements conditions are for instance form-fits used, data filtering schemes employed and other important information concerning the test set such as warm-up time and date of calibration.

3.15
national standard
standard recognized by a national decision to serve, in a country, as the basis for assigning values to other standards of the quantity concerned

[SOURCE: ISO/IEC Guide 99:2007, 5.3, modified – The first preferred term "national measurement standard" has been deleted, and the definition has been rephrased.]

3.16
national standards laboratory
laboratory which maintains the national standard

3.17
operating range
range of conditions under which the geometry test set is designed to perform within the stated expanded uncertainty

Note 1 to entry: Such conditions include the diameter of the fibre being measured and environmental conditions, such as temperature.

3.18
reference standard
artefact measured at a calibration laboratory, with the measurement traceable to national standards

3.19
scaling factor
ratio of the known standard values for a calibration standard to the values indicated by the geometry test set when no correction offsets are applied

3.20
standard uncertainty
u
uncertainty of a measurement result expressed as a standard deviation

Note 1 to entry: For further information, see Annex A and ISO/IEC Guide 98-3.

3.21
traceability
ability to demonstrate, for a measurement result or a geometry test set, a calibration chain originating from a national standard

Note 1 to entry: Geometry test sets calibrated by the procedures in this document are traceable. Direct traceability of the measurement results either to a national standards laboratory or to an accredited calibration laboratory need to be demonstrated. Such traceability includes the calibration schedules of all artefacts in the calibration chain and detailed calculations of all (cumulative) transfer uncertainties in the calibration chain.

Note 2 to entry: The use of a working standard alone to compare or monitor geometry test set calibration cannot establish or re-establish traceability, but can only extend the duration of the traceability certification if no change is found.

3.22
transfer standard
standard that is calibrated against a reference standard and is used for calibrating geometry test sets

3.23
transfer uncertainty
estimate characterizing the uncertainty of a measurement caused by uncertainties in the transfer process, at the given confidence level (such as changes in environmental conditions)

Note 1 to entry: These uncertainties may arise from the calibration standards used as well as from the geometry test set.

3.24
working standard
standard that is used on a routine basis to calibrate or check measuring instruments

4 General information and preparation for calibration

4.1 Geometrical parameters of optical fibres

It is necessary to characterize the geometrical properties of optical fibres in order to ensure satisfactory mechanical and optical performance. The geometrical parameters measured by the types of test sets consist of the following:

a) cladding (reference surface) diameter;
b) cladding non-circularity;
c) core/cladding concentricity error.

4.2 Description of geometry test sets

End face image, or grey-scale, test sets usually comprise an optical microscope, an illumina-tion source, an electronic image recording device, such as a camera, and a means of storing image data for processing by digital computer. A second illumination source is usually employed to launch light into the other end of the fibre. This enables the position of the fibre core also to be measured. A typical measurement sequence is as follows: a cleaved fibre end is positioned in the measurement port of the instrument and an image of the fibre end is formed on the camera. The image of the fibre is focused, usually under automatic computer control, digitized, and then transferred to a computer, which determines the geometrical parameters of the fibre.

The quality of the fibre end is critical in this method, and the presence of cleave damage, such as chips or edge roughness, can seriously affect the measurement. It is thus usual to employ data-filtering methods to reduce the sensitivity of the measured result to the presence of cleave damage.

4.3 Calibration standard requirements

The calibration procedure detailed in this document requires the use of traceable calibration artefacts. These artefacts consist of a calibrated fibre end and a chromium-on-glass mask. Their nominal dimensions are discussed in 5.3.3 and 5.5.

5 Calibration

5.1 General

The calibration procedure comprises the following two operations.

a) The magnification, or scaling factor, of the imaging system is calibrated. This is a similar process to conventional calibration methods for optical microscopes, except that, in this case, a two-dimensional calibration is required.

b) A correction offset is determined. This offset is required to correct for systematic effects such as diffraction at the fibre edge, differences between the way the calibration artefact is calibrated and the method of measurement in the test set, and distortion of the image of the fibre edge by camera sampling.

Worked examples for the determination of calibration factors are given in Annex B.

The calibration will be valid when applied to measurements in the following way:

– the scaling factors are applied multiplicatively to the raw data from the camera, before applying form-fits and computing the cladding diameter of the fibre under test;

– the correction offset is applied additively to the computed cladding diameter of the fibre under test.

NOTE 1 The choice of an edge-setting criterion defining the position of the cladding edge is important, and calibration applies only to measurements using the same criterion as that used at the time of calibration.

NOTE 2 In certain circumstances, it has been found sufficient to calibrate only the scaling factor using a fibre or chromium-on-glass standard. This approach, however, can lead to increased uncertainties when measuring fibres that are of significantly different diameter from the calibration standard used.

5.2 Rationale for calibration of geometry test sets

5.2.1 General

The measurement of cladding diameter is common to most types of geometry test sets, so calibration of this parameter is very important in comparing test sets of different types. This document, however, details only the calibration of test sets that perform end-face image analysis.

Basically, calibration is achieved by exposing the test set to independent geometrical calibration standards. It is these standards that form the calibration chain and, therefore, contribute to the transfer uncertainty.

The procedure is detailed in 5.3. The complete calibration chain is illustrated in Figure 1.

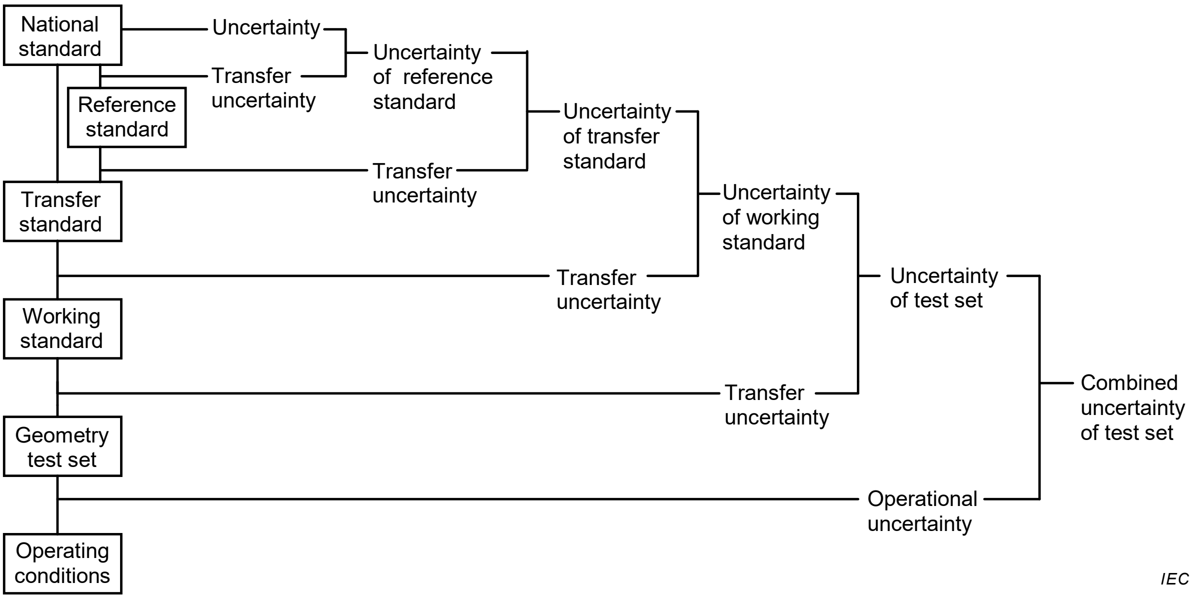

Figure 1 – Example of a calibration chain and the accumulation of uncertainties

Calibration of the core/cladding concentricity error and non-circularity measurement is not described, as there are no suitable standard reference materials available at the time of writing. However, procedures enabling estimation of the uncertainties obtained in the measurement of these parameters are given in Annex G and Annex H respectively.

5.2.2 Verification of calibration state

For routine verification, such as may frequently be carried out on geometry test sets in use, it is sufficient to check (but not to reset) the state of calibration of the geometry test sets using a working standard. The working standard may be a fibre or a chrome-on-glass mask.

A procedure for generation of a working standard is given in Annex F.

The distinction between checking the state of calibration and the calibration itself shall be clearly made. While it is sufficient to establish stability of the geometry test set using the working standard, this is not a substitute for full calibration.

The use of a working standard allows continued traceability to national standards to be claimed, if it can be satisfactorily established that the existing instrument state, correction factors, and so on, are sufficient to provide geometry results within a specified uncertainty and without alteration. This simply means that the geometry test set has remained stable since the last calibration.

Continued traceability can be claimed on a calibrated test set provided that the measured values for the working standard agree with its calibrated values within the uncertainties.

Calibration is essential in the commissioning of geometry test sets, whereas a working standard is used for routine calibration checking.

The procedure for calibration checking is described in 5.4.

5.3 Calibration procedure

5.3.1 General advice and organization

Ensure that the environmental conditions are commensurate with the working environment as specified by the manufacturer. Employ good metrological practices at all times.

Ensure that all calibration standards used in the calibration are calibrated according to a documented programme with traceability to national standards laboratories or to accredited standards laboratories. If possible, maintain more than one standard on each hierarchical level of the calibration chain, so that the performance of standards can be verified by comparisons on the same level.

Develop a documented measurement procedure for each type of calibration performed, giving step-by-step operating instructions and equipment to be used. Use pro-forma result sheets, uncertainty budgets and calibration certificates (see Clause 7).

Operate a quality system appropriate to the range of measurements. Ensure that there is independent scrutiny of measurement results, intermediate calculations and calibration certificates are prepared.

5.3.2 Test requirements

a) Perform all tests at a temperature and relative humidity that are within the manufacturer’s specification for the test set.
b) Allow sufficient time for the geometry test set and test equipment to reach thermal equilibrium with the environment in accordance with the manufacturer's recommendations for the test set and the calibration standards used, before commencing the calibration procedure.
c) Set up the geometry test set to the appropriate settings for calibration procedures, as recommended by the manufacturer.
d) Ensure, where possible, that all accessible optical surfaces and calibration standards are clean before measurement.

5.3.3 Calibration standard requirements

The use of calibration standards which are traceable to national standards laboratories is mandatory. The calibration procedure requires the use of the following.

a) A calibrated measurement scale. This is a chromium-on-glass mask with a pattern, typically, of dots, lines, circles or annuli.
b) A fibre end with calibrated cladding diameter. The fibre should be of similar material to and within 5,0 µm of the nominal cladding diameter of the fibres to be measured by the test set and have a non-circularity of less than 0,5 %.

The calibrated fibre end shall not be re-cleaved. This is due to variations of diameter along the length of the fibre.

If the fibre end becomes damaged or cannot be cleaned sufficiently, it should not be used for the purpose of calibration.

For calibration checking (see 5.4), the standard may be either a fibre or a chromium-on-glass pattern with traceable geometry values.

5.3.4 Determination of calibration factors

5.3.4.1 General

A derivation of the calibration factors used is given in Annex B.

5.3.4.2 Scaling factor

To calibrate the scaling factor, use a chromium-on-glass mask. This may comprise an array of dots or lines, or an annular structure. The principle of calibration is to measure the distance between graduations.

NOTE The uniformity of the scaling factor over the field of view of the imaging system (known as "spatial linearity") will affect the uncertainty that can be transferred to measurements on fibres and also to measurements of core/cladding concentricity error. A method for estimating spatial linearity is described in 5.5.

The scaling factors for the x and y axes of the camera are given by:

$$S_\mathrm{x} = \frac{D\mathrm{x}_\mathrm{c}}{D\mathrm{x}_\mathrm{m}} \tag{2}$$

$$S_\mathrm{y} = \frac{Dy_\mathrm{c}}{Dy_\mathrm{m}} \tag{3}$$

where

$D\mathrm{x}_\mathrm{m}$ is the measured spacing of graduations along the x-axis;

$D\mathrm{y}_\mathrm{m}$ is the measured spacing of graduations along the y-axis;

$D\mathrm{x}_\mathrm{c}$ is the calibrated spacing of graduations along the x-axis;

$D\mathrm{y}_\mathrm{c}$ is the calibrated spacing of graduations along the y-axis.

The procedure to measure the distance between graduations will depend on the type of chrome mask used, as follows.

a) Regular array of dots or lines

Form an image of the array in a manner consistent with normal operation of the test set. Measure the distances between graduations in two orthogonal directions, these being parallel to the scan axes of the camera. The distance over which calibration is effected should be within 5 µm of the nominal diameter of the fibres to be measured by the test set. It is desirable to align the axes of the array to be parallel to the scan axes of the camera. However, if they are not so aligned, compensation for the angular misalignment needs to be applied.

b) Annulus

Form an image of the annulus in a manner consistent with normal operation of the test set. Apply elliptical form fits to the inner and outer edges of the annulus. Determine the measured diameters $D\mathrm{x}_\mathrm{m}$ and $D\mathrm{y}_\mathrm{m}$ along the x and y axes as follows:

$$D\mathrm{x}_\mathrm{m} = \frac{D\mathrm{x}_\mathrm{inner} + D\mathrm{x}_\mathrm{outer}}{2} \tag{4}$$

and

$$D\mathrm{y}_\mathrm{m} = \frac{D\mathrm{y}_\mathrm{inner} + D\mathrm{y}_\mathrm{outer}}{2} \tag{5}$$

where

$D\mathrm{x}_\mathrm{inner}$ is the measured diameter of the inner annulus along the x-axis;

$D\mathrm{y}_\mathrm{inner}$ is the measured diameter of the inner annulus along the y-axis;

$D\mathrm{x}_\mathrm{outer}$ is the measured diameter of the outer annulus along the x-axis;

$D\mathrm{y}_\mathrm{outer}$ is the measured diameter of the outer annulus along the y-axis.

The diameter of the annulus should be within 5 µm of the nominal diameter of the fibres to be measured by the test set. If, for convenience of use, it is assumed that $D\mathrm{x}_\mathrm{m}$ equals $D\mathrm{y}_\mathrm{m}$, any non-circularity in the annulus will affect the determination of the uncertainty in subsequent fibre non-circularity measurements (see 5.7).

Calculate the uncertainty in the determination of the scaling factors using Clause 6.

5.3.4.3 Correction offset

To calibrate the correction offset, a calibrated fibre is required. Form an image of the fibre end in a manner consistent with normal operation of the test set and apply a form-fitting algorithm to the fibre edge. Determine the correction offset O as follows:

$$O = D_{\mathrm{P,F}} - D'_{\mathrm{P,F}} \times S \tag{6}$$

where

$D_{\mathrm{P,F}}$ is the calibrated diameter of the fibre;

$D'_{\mathrm{P,F}}$ is the measured diameter of the fibre (scaling factor not applied);

P stands for "parent";

F stands for "fibre".

And S, the mean scaling factor, is:

$$S = \frac{S_\mathrm{x} + S_\mathrm{y}}{2}$$

Thus $D'_{\mathrm{P,F}} \times S$ is equal to the measured diameter of the fibre, in micrometres.

Calculate the uncertainty in the determination of the correction offset using Clause 6.

5.4 Check calibration procedure

This procedure is used for checking the calibration of a geometry test set. The procedure is not used for determining calibration factors but may be used to check for test set stability since the last calibration was performed.

As long as the geometry test set has already been calibrated and measurement of a working standard does not reveal a geometry uncertainty greater than the permitted total uncertainty, the claim of traceability may be extended.

a) Ensure that the test requirements given in 5.3.2 have been met.

b) Present the working standard to the geometry test set under consideration.

c) In the case where the working standard is
  - a fibre: measure the mean cladding diameter;
  - a chromium-on-glass mask: measure the distance between graduations.

Compare the measured values with the reference values and record any differences. It is necessary to repeat the measurement several times to statistically reduce uncertainty in the mean measured value.

5.5 Spatial linearity

The uncertainty in the measurement of fibres the diameter of which differs by more than 5 µm from that of the fibre used for calibration may be estimated in one of two ways.

a) Measure a chromium-on-glass artefact at different positions within the field of view.

b) Measure the spacing between graduations of an array of lines or dots over the whole field of view.

In either case, the linear dimension of the artefact or the interval shall be less than one-quarter of the diameter of the calibration fibre used. If method a) is used, only a nominal calibration of the artefact is necessary. If method b) is used, it is necessary to use an artefact that has each interval calibrated.

A variation in the scaling factor over the field of view indicates a source of uncertainty in the calibration of the test set scaling factor. The importance of this uncertainty will depend on the range of fibre diameters to be measured on the calibrated test set. Estimate the magnitude of the uncertainty and add it to the total scaling factor uncertainty u_S, derived in 6.2.2.

5.6 Calibration of core/cladding concentricity error measurement

Core/cladding concentricity error is defined as the distance between the centres of the core and cladding of a fibre.

At the time of writing, there are no standard reference materials (SRM) available from standards laboratories for direct calibration of this parameter. A procedure is given in Annex G describing how to estimate the uncertainty obtained in a concentricity error measurement.

5.7 Calibration of non-circularity measurement

Non-circularity is defined as the difference in radial distance of edge points that are respectively furthest from and closest to the fitted centre, divided by the fitted radius. In the case of an ellipse form-fit, non-circularity is the difference between the major and minor axes, divided by their mean.

At the time of writing, there are no standard reference materials (SRM) available from standards laboratories for direct calibration of this parameter. A procedure is given in Annex H describing how to estimate the uncertainty obtained in a non-circularity measurement.

6 Evaluation of uncertainties

6.1 General

In Clause 6, the reporting of uncertainties in the calibration of a test set and in subsequent measurements is discussed. The analysis is based on the statistical mathematics given in Annex D. It is important to choose a confidence level at which to calculate uncertainties and use the appropriate values for the coverage factor in each calculation (see definition 3.10 and Clause D.3).

The uncertainty of calibration of the test set is discussed in 6.2. The uncertainty in the measurement of a fibre is discussed in 6.3. The uncertainty in the measurement of a chromium-on-glass mask is discussed in 6.4.

Worked examples for the determination of uncertainties are given in Annex E.

6.2 Evaluation of uncertainty in test set calibration

6.2.1 General

The calibration procedure (see 5.3.4) comprises two operations. First, a scaling factor is determined and then a correction offset factor is determined. Sources of uncertainty in both of these parameters shall be evaluated to estimate the calibration uncertainty of the test set.

6.2.2 Uncertainty in scaling factor

6.2.2.1 General

The following terms are used:

S	scaling factor
$D_{\mathrm{P,C}}$	calibrated spacing of graduations of parent chromium standard
$u_{\mathrm{P,C}}$	uncertainty in calibration of parent chromium standard
$D'_{\mathrm{P,C}}$	measured spacing of graduations of parent chromium standard (raw data)
$u'_{\mathrm{P,C}}$	statistical uncertainty in measurement of parent chromium standard (raw data)
$u_{\mathrm{Tr,P,C}}$	transfer uncertainty of parent chromium standard
n_{C}	number of measurements

where P stands for "parent" and C for "chromium".

The determination of the scaling factor is described in 5.3.4.2 and is given in terms of two scaling factors, one for each of the two camera axes. For the purpose of estimating the uncertainty in the scaling factor, the two scaling factors may be combined to give the following expression:

$$S = \frac{D_{\mathrm{P,C}}}{D'_{\mathrm{P,C}}} \qquad (7)$$

The uncertainty u_{S} in the scaling factor consists of the calibration uncertainty $u_{\mathrm{P,C}}$ of the parent chromium standard, any changes $u_{\mathrm{Tr,P,C}}$ that may have occurred in the parent chromium standard since its calibration, and the statistical uncertainty $u'_{\mathrm{P,C}}$ in the measurement of the parent chromium standard on the test set.

The relative uncertainty u_{S} in the scaling factor is given by:

$$u_{\mathrm{S}} = \sqrt{\frac{u_{\mathrm{Tr,P,C}}{}^2 + u_{\mathrm{P,C}}{}^2 + \left(\frac{u'_{\mathrm{P,C}} \times S}{\sqrt{n_{\mathrm{C}}}}\right)^2}{D_{\mathrm{P,C}}{}^2}} \qquad (8)$$

6.2.2.2 Determination of $u_{\mathrm{P,C}}$

The uncertainty $u_{\mathrm{P,C}}$ in the calibration of the parent standard may be determined from the parent's calibration certificate or data sheet. Using the expanded uncertainty $U_{\mathrm{P,C}}$ of the parent, calculate $u_{\mathrm{P,C}}$ as follows:

$$u_{\mathrm{P,C}} = \frac{U_{\mathrm{P,C}}}{k} \qquad (9)$$

where k is the coverage factor.

Determine k from the parent's calibration certificate.

6.2.2.3 Determination of $u_{\mathrm{Tr,P,C}}$

The transfer uncertainty may be due to factors affecting the calibration of the parent chromium standard, for example ageing, temperature-induced changes and cleanliness. Estimate the transfer uncertainty using Equation (A.5).

6.2.2.4 Determination of $u'_{\mathrm{P,C}}$

Determine the statistical uncertainty in measurement of the parent chromium standard using Equation (A.2).

6.2.3 Uncertainty in offset correction factor

6.2.3.1 General

The following terms are used:

S	scaling factor
$D_{\mathrm{P,F}}$	calibrated diameter of parent fibre standard
$u_{\mathrm{P,F}}$	calibration uncertainty of parent fibre standard
$u'_{\mathrm{P,F}}$	statistical uncertainty in measurement of parent fibre standard (raw data)
$u_{\mathrm{Tr,P,F}}$	transfer uncertainty of parent fibre standard
n_{F}	number of measurements

where P stands for "parent" and F for "fibre".

The determination of the offset correction factor is described in 5.3.4.3. The offset O is given by:

$$O = D_{\mathrm{P,F}} - D'_{\mathrm{P,F}} \times S \tag{10}$$

The uncertainty u_{O} in the offset factor consists of the uncertainty $u_{\mathrm{P,F}}$ in the calibration of the parent fibre standard, any changes $u_{\mathrm{Tr,P,F}}$ that may have occurred in the fibre standard since its calibration and the statistical uncertainty $u'_{\mathrm{P,F}}$ in the measurement of the parent fibre standard on the test set.

The uncertainty u in the offset is given by:

$$u_{\mathrm{O}} = \sqrt{u_{\mathrm{P,F}}^2 + u_{\mathrm{Tr,P,F}}^2 + \left(\frac{u'_{\mathrm{P,F}} \times S}{\sqrt{n_{\mathrm{F}}}}\right)^2} \tag{11}$$

NOTE The uncertainty u_{S} in the scaling factor is not included in the derivation of Equation (11). This is because error in the scaling factor is compensated for in the determination of the correction offset factor, according to Equation (10). However, it will contribute to the uncertainty in fibre diameter measurement when the diameter of the fibre being measured is different from the diameter of the calibration fibre that was used in the determination of the offset correction factor (see 6.3).

6.2.3.2 Determination of $u_{\mathrm{P,F}}$

The uncertainty $u_{\mathrm{P,F}}$ of the parent may be determined from the expanded uncertainty $U_{\mathrm{P,F}}$ quoted on the parent's calibration certificate or data sheet. Express this as a standard uncertainty $u_{\mathrm{P,F}}$ as follows:

$$u_{\mathrm{P,F}} = \frac{U_{\mathrm{P,F}}}{k} \tag{12}$$

where k is the coverage factor.

Determine k from the parent's calibration certificate.

6.2.3.3 Determination of $u_{\mathrm{Tr,P,F}}$

The transfer uncertainty may be due to factors affecting the calibration of the parent fibre standard, for example ageing, temperature induced changes, and cleanliness. Estimate the transfer uncertainty using Equation (A.5).

6.2.3.4 Determination of $u'_{\mathrm{P,F}}$

Determine the statistical uncertainty in measurement of the parent fibre standard using Clause A.2.

6.3 Evaluation of uncertainty in fibre measurement

6.3.1 General

The following terms are used:

$D_{\mathrm{P,F}}$	calibrated diameter of parent fibre standard used in offset determination
$D_{\mathrm{I,F}}$	diameter of infant fibre (to be determined)
$D'_{\mathrm{I,F}}$	measured diameter of infant fibre (raw data)
$u'_{\mathrm{I,F}}$	statistical uncertainty in measurement of infant fibre (raw data)
$u_{\mathrm{Op,I,F}}$	operational uncertainty of infant fibre
n_{F}	number of measurements

where I stands for "infant" and F for "fibre".

The measured diameter of the infant fibre after calibration is given by:

$$D_{\mathrm{I,F}} = D'_{\mathrm{I,F}} \times S + O \tag{13}$$

The uncertainty $u_{\mathrm{I,F}}$ in the measurement consists of the uncertainty u_{S} in the scaling factor, the uncertainty u_{O} in the offset factor and the statistical uncertainty $u'_{\mathrm{I,F}}$ in the measurement of the infant fibre on the test set. Further, if the measurement depends on changes in conditions of the operating range from those existing at the time of calibration, these changes shall be taken into account in the form of an operational uncertainty $u_{\mathrm{Op,I,F}}$. Uncertainty in the determination of the scaling factor contributes to the uncertainty in the determination of the fibre diameter when the diameter of the fibre under test is different from the diameter of the calibration fibre that was used in the determination of the correction offset factor (see 6.2.3). This is included as the final term in the following expression.

The uncertainty $u_{\mathrm{I,F}}$ in the measured diameter of the infant fibre is given by:

$$u_{\mathrm{I,F}} = \sqrt{u_{\mathrm{O}}^2 + u_{\mathrm{Op,I,F}}^2 + \left(\frac{u'_{\mathrm{I,F}} \times S}{\sqrt{n_{\mathrm{F}}}} \right)^2 + \left(D'_{\mathrm{I,F}} \times S - D_{\mathrm{P,F}} \right)^2 \times u_{\mathrm{S}}^2} \tag{14}$$

6.3.2 Determination of $u_{\mathrm{Op,I,F}}$

The operational uncertainty is due to operating conditions that are different from those existing at the time of calibration, for example cleave quality, cleanliness and operating temperature. Estimate the operational uncertainty using Equation (A.5).

6.3.3 Determination of $u'_{\mathrm{I,F}}$

Determine the statistical uncertainty in measurement of the infant fibre using Clause A.2.

6.4 Evaluation of uncertainty in chromium mask measurement

6.4.1 General

The following terms are used:

$D_{\mathrm{I,C}}$	spacing of graduations of infant chromium mask (to be determined)
$D'_{\mathrm{I,C}}$	measured spacing of graduations of infant chromium mask (raw data)
$u'_{\mathrm{I,C}}$	statistical uncertainty in measurement of infant chromium mask (raw data)
$u_{\mathrm{Op,I,C}}$	operational uncertainty of infant chromium mask
n_{C}	number of measurements

where I stands for "infant" and C for "chromium".

The measured diameter of the infant chromium mask after calibration is given by:

$$D_{\mathrm{I,C}} = D'_{\mathrm{I,C}} \times S \tag{15}$$

The uncertainty $u_{\mathrm{I,C}}$ in the measured diameter consists of the relative uncertainty u_{S} in the scaling factor and the statistical uncertainty $u'_{\mathrm{I,C}}$ in the measurement of the infant chromium mask on the test set. Further, if the measurement depends on changes in operating conditions from those existing at the time of calibration, these changes shall be taken into account in the form of an operational uncertainty $u_{\mathrm{Op,I,C}}$.

The uncertainty $u_{\mathrm{I,C}}$ in the measured diameter of the infant chromium mask is:

$$u_{\mathrm{I,C}} = \sqrt{u_{\mathrm{Op,I,C}}^2 + \left(\frac{u'_{\mathrm{I,C}} \times S}{\sqrt{n_{\mathrm{C}}}} \right)^2 + \left(D'_{\mathrm{I,C}} \times u_{\mathrm{S}} \right)^2} \tag{16}$$

6.4.2 Determination of $u_{\mathrm{Op,I,C}}$

The operational uncertainty is due to operating conditions that are different from those existing at the time of calibration, for example cleave quality, cleanliness and operating temperature. Estimate the operational uncertainty using Equation (A.5).

6.4.3 Determination of $u'_{\mathrm{I,C}}$

Determine the statistical uncertainty in measurement of the infant chromium mask using Clause A.2.

6.5 Summary

The uncertainty in the calibration of the test set has been evaluated in terms of the scaling factor uncertainty and the offset factor uncertainty, in 6.2.2 and 6.2.3 respectively.

The uncertainties in the measurement of a test fibre and a chromium-on-glass mask are evaluated in 6.3 and 6.4 respectively.

The statement of uncertainty in the measurement on a fibre or chromium mask includes the uncertainties of the calibration standards used to calibrate the test set, the statistical measurement uncertainties and any other additional measurement uncertainties.

7 Documentation

7.1 Records

Proper records shall be kept when a geometry test set is calibrated according to this procedure. These records shall include the following:

a) description of the test set and unique identification (serial number);

b) date on which the calibration was performed;

c) results obtained from the calibration process (see Clause 6);

d) identification of the calibration procedure followed;

e) unique identification of all calibration standards used and certification demonstrating traceability;

f) identification of personnel performing the calibration;

g) statement of uncertainties involved in calibrating the test set and of their cumulative effect on the uncertainties in the scaling and offset factors (see Clause 6);

h) instrument state, such as threshold levels for edge point selection, criteria for point rejection and types of form-fit applied.

Annex A
(normative)

Mathematical basis for measurement uncertainty calculations

A.1 General

Annex A summaries the form of evaluating, combining and reporting the uncertainty of measurement. It is based on the ISO/IEC Guide 98-3. It does not relieve the need to consult this guide for more advice.

This document distinguishes two types of evaluation of uncertainty of measurement. Type A is the method of evaluation of uncertainty by the statistical analysis of a series of measurements on the same measurand. Type B is the method of evaluation of uncertainty based on other knowledge.

A.2 Type A evaluation of uncertainty

The type A evaluation of standard uncertainty can be applied when several independent observations have been made for a quantity under the same conditions of measurement.

For a quantity X estimated from n independent repeated observations X_k, the arithmetic mean is:

$$\overline{X} = \frac{1}{n}\sum_{k=1}^{n} X_\mathrm{k} \tag{A.1}$$

This mean is used as the estimate of the quantity, that is $x = \overline{X}$. The experimental standard deviation of the observations is given by:

$$s(X) = \left[\frac{1}{n-1}\sum_{k=1}^{n}\left(X_\mathrm{k} - \overline{X}\right)^2\right]^{1/2} \tag{A.2}$$

where

$\overline{X}$ is the arithmetic mean of the observed values;

X_k are the measurement samples of a series of measurements;

n is the number of measurements; it is assumed to be large, for example, $n \geq 10$.

The type A standard uncertainty $u_{\mathrm{typeA}(x)}$ associated with the estimate x is the experimental standard deviation of the mean:

$$u_{\mathrm{typeA}}(x) = s(\overline{X}) = \frac{s(X)}{\sqrt{n}} \tag{A.3}$$

A.3 Type B evaluation of uncertainty

The type B evaluation of standard uncertainty is the method of evaluating the uncertainty by means other than the statistical analysis of a series of observations. It is evaluated by scientific judgement based on all available information on the variability of the quantity.

If the estimate x of a quantity X is taken from a manufacturer's specification, calibration certificate, handbook, or other source and its quoted uncertainty $U(x)$ is stated to be a multiple k of a standard deviation, the standard uncertainty $u(x)$ is simply the quoted value divided by the multiplier.

$$u(x) = U(x) / k \tag{A.4}$$

If only upper and lower limit X_{max} and X_{min} can be estimated for the value of the quantity X, a rectangular probability distribution is assumed.

The standard uncertainty is

$$u(x) = \frac{\left(\left|X_{\text{max}} - x\right|, \left|X_{\text{min}} - x\right|\right)_{\text{MAX}}}{\sqrt{3}} \tag{A.5}$$

The contribution to the standard uncertainty associated with the output estimate y resulting from the standard uncertainty associated with the input estimate x is

$$u(y) = c \times u(x) \tag{A.6}$$

where c is the sensitivity coefficient associated with the input estimate x, that is the partial derivative of the model function $y(x)$, evaluated at the input estimate x.

$$c = \frac{\partial y}{\partial x} \tag{A.7}$$

The sensitivity coefficient c describes the extent to which the output estimate y is influenced by variations of the input estimate x. It can be evaluated by Equation (A.7) or by using numerical methods, that is by calculating the change in the output estimate y due to a change in the input estimate x from a model function. Sometimes it may be more appropriate to find the change in the output estimate y due to the change of x from an experiment.

A.4 Determining the combined standard uncertainty

The combined standard uncertainty is used to collect a number of individual uncertainties into a single number. The combined standard uncertainty is based on statistical independence of the individual uncertainties; it is calculated by root-sum-squaring all standard uncertainties obtained from type A and type B evaluation:

$$u_{\text{c}}(y) = \sqrt{\sum_{i=1}^{n} u_i^2(y)} \tag{A.8}$$

where

i	is the current number of individual contribution;
$u_{\text{i}}(y)$	are the standard uncertainty contributions;
n	is the number of uncertainties.

NOTE It is acceptable to neglect uncertainty contributions to this equation that are smaller than 1/10 of the largest contribution, because squaring them will reduce their significance to 1/100 of the largest contribution.

When the quantities above are to be used as the basis for further uncertainty computations, then the combined standard uncertainty, u_{c}, can be re-inserted into Equation (A.8). Despite its partially type A origin, u_{c} should be considered as describing an uncertainty of type B.

A.5 Reporting

In calibration reports and technical data sheets, combined standard uncertainties shall be reported in the form of expanded uncertainties, together with the applicable level of confidence. Correction factors or deviations shall be reported. The expanded uncertainty U is obtained by multiplying the standard uncertainty $u_{\mathrm{c}}(y)$ by a coverage factor k:

$$U = k \times u_c(y) \tag{A.9}$$

Annex B
(informative)

Derivation of calibration factors

B.1 Derivation of scaling factors

Refer to 5.3.4.2.

Terms used:

$D\text{x}_\text{c}$	calibrated spacing of graduations of the mask along the x-axis;
$D\text{y}_\text{c}$	calibrated spacing of graduations of the mask along the y-axis;
$D\text{x}_\text{m}$	measured spacing of graduations of the mask along the x-axis;
$D\text{y}_\text{m}$	measured spacing of graduations of the mask along the y-axis;
$D\text{x}_\text{inner}$	measured diameter of the inner annulus along the x-axis;
$D\text{y}_\text{inner}$	measured diameter of the inner annulus along the y-axis;
$D\text{x}_\text{outer}$	measured diameter of the outer annulus along the x-axis;
$D\text{y}_\text{outer}$	measured diameter of the outer annulus along the y-axis;

where the x and y axes are defined as the scan axes of the camera.

Figure B.1 shows how the measured graduation spacings $D\text{x}_\text{m}$ and $D\text{y}_\text{m}$ of a mask consisting of a grid of lines are defined.

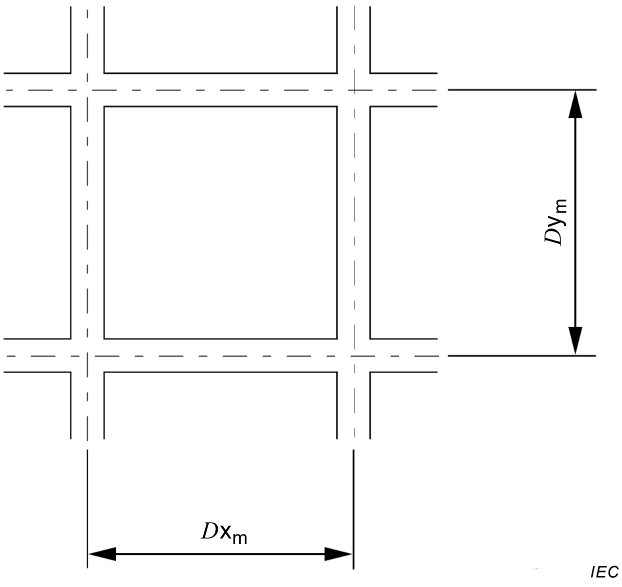

Figure B.1 – Representation of a grid calibration mask

The inner and outer diameters of the annulus along the x and y axes are derived from elliptical form-fits applied to the inner and outer edges of the annulus. Figure B.2 shows how the measured diameters of an annulus are defined. The graduation spacings for the annulus are given by:

$$D\text{x}_\text{m} = \frac{D\text{x}_\text{inner} + D\text{x}_\text{outer}}{2} \tag{B.1}$$

$$D\mathrm{y_m} = \frac{D\mathrm{y_{inner}} + D\mathrm{y_{outer}}}{2} \tag{B.2}$$

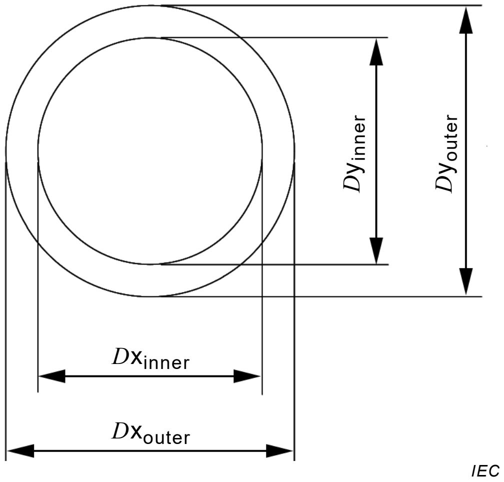

Figure B.2 – Representation of an annulus calibration mask

The scaling factors S_x and S_y of the scan axes of the camera for both mask configurations are given by:

$$S_\mathrm{x} = \frac{D\mathrm{x_c}}{D\mathrm{x_m}} \tag{B.3}$$

$$S_\mathrm{y} = \frac{D\mathrm{y_c}}{D\mathrm{y_m}} \tag{B.4}$$

B.2 Derivation of correction offset factor

Refer to 5.3.4.3.

The correction offset is required to correct for systematic effects such as diffraction at the fibre edge. It is defined as the difference between the calibrated diameter D_cal of a fibre and its measured diameter D_meas, after the scaling factor, but no offset, has been applied. The offset (O) is given by:

$$O = D_\mathrm{cal} - D_\mathrm{meas} \tag{B.5}$$

Figure B.3 illustrates the relationship between the calibrated and measured diameters.

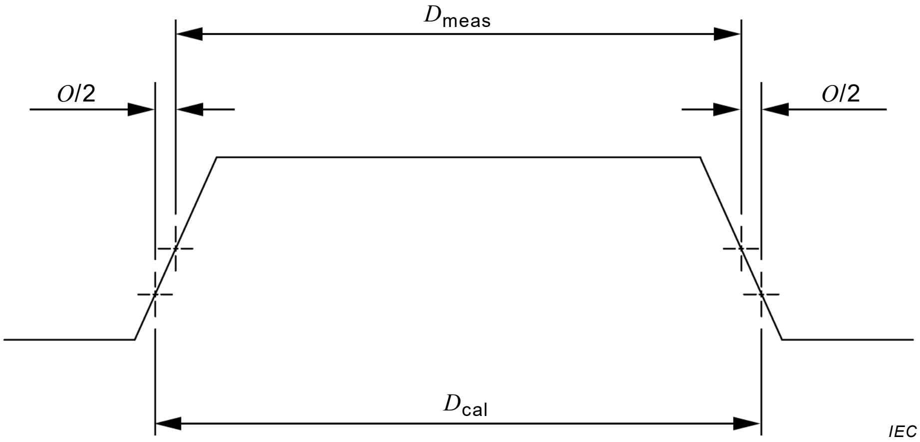

Figure B.3 – Derivation of correction offset

Annex C
(informative)

Examples for the determination of calibration factors

C.1 Example of determination of scaling factor

Refer to 5.3.4.2.

Let:

$D\mathrm{x}_\mathrm{c}$ = 125,60 µm (calibrated spacing of graduations along the x-axis);
$D\mathrm{y}_\mathrm{c}$ = 125,60 µm (calibrated spacing of graduations along the y-axis);
$D\mathrm{x}_\mathrm{m}$ = 125,46 (measured spacing of graduations along the x-axis, raw data);
$D\mathrm{y}_\mathrm{m}$ = 124,84 (measured spacing of graduations along the y-axis, raw data).

From Equations (2) and (3), the scaling factors S_x and S_y are:

$$S_\mathrm{x} = 1{,}001\ 1 \qquad S_\mathrm{y} = 1{,}006\ 1$$

C.2 Example of determination of offset correction factor

Refer to 5.3.4.3.

Let:

$D_\mathrm{P,F}$ = 125,64 µm (calibrated diameter of fibre)
$D'_\mathrm{P,F}$ = 124,77 (measured diameter of fibre, raw data)
S = (1,001 1 + 1,006 1)/2 = 1,003 6 (see Clause C.1)

From Equation (6), the offset correction factor is:

$$O = 0{,}42\ \mu\mathrm{m}$$

Annex D
(informative)

Calculation of uncertainties

D.1 General

D.1.1 Overview

The uncertainty in the result of a measurement generally consists of several components. These may be grouped broadly into two categories according to the method used to evaluate them:

– type A: uncertainties which are evaluated by statistical methods;

– type B: uncertainties which are evaluated by other means.

Annex D describes examples on how to evaluate these uncertainties. Type of uncertainty and initial calculation are described in Annex A.

D.1.2 Examples of type B evaluation of uncertainty

Example A: Where the uncertainty is caused by an influencing quantity (such as temperature changes) and, in the course of a number of measurements of the same quantity, remains constant or varies in a predictable way, the uncertainty may be calculated as follows:

a) determine the change in the influencing quantity;

b) obtain the upper and lower limits of uncertainty in the measured value of a parameter by multiplying the change in the influencing quantity by the instrument dependence on that quantity. Calculate the standard uncertainty using Equation (A.5).

Example B: In the case where the effect of an influencing quantity is difficult to quantify, then experience and judgement shall be used. For example, the effect of contamination of the fibre end being measured cannot readily be determined but experience in such measurements will enable the likely uncertainty to be estimated.

Example C: The uncertainty that is associated with a calibration standard will be quoted on the calibration certificate for that standard. If the uncertainty is specified as upper and lower limits, the standard uncertainty may be determined using Equation (A.5). If the uncertainty is specified at a particular confidence level, the standard uncertainty at, for example, 68,3 % is equal to the quoted uncertainty divided by the appropriate coverage factor.

D.2 Combining sources of uncertainty

D.2.1 General

Several sources of standard uncertainty may, assuming statistical independence, be combined to give a single uncertainty u_{com} as follows:

$$u_{\text{com}} = \sqrt{\sum_{\text{i}} u_{\text{i}}^2} \tag{D.1}$$

where u_{i} is the standard uncertainty, one of n uncertainty sources.

When several standard uncertainties are combined, it is essential that each component of uncertainty be specified at the same confidence level. In order to specify the expanded uncertainty U_{com} at a confidence level other than that used for each individual uncertainty, each component of uncertainty u_{i} is first multiplied by the appropriate coverage factor k_{i}

corresponding to the number of samples used in the determination of that uncertainty, and then combined as follows:

$$U_{\mathrm{com}} = \sqrt{\sum_{\mathrm{i}} k_{\mathrm{i}}^2 \times u_{\mathrm{i}}^2} \tag{D.2}$$

NOTE If the sample sizes for each component of uncertainty are all large, the expanded uncertainty is obtained by multiplying the combination of individual uncertainties, according to Equation (A.8), by a single coverage factor.

For small samples, the coverage factor k is determined by taking k equal to a t-factor obtained from Student's t distribution for the particular number of measurements.

D.2.2 Example of combining several sources of uncertainty

Consider the following values for three individual components of uncertainty:

u_1 = 0,052 µm	n_1 = 8
u_2 = 0,069 µm	n_2 = 12
u_3 = 0,034 µm	n_3 = 9

From Table D.1, the corresponding values for k at a confidence level of 95,5 % are:

k_1 = 2,43
k_2 = 2,25
k_3 = 2,37

Using Equation (D.2) the expanded total uncertainty at 95,5 % confidence level is given by:

$$U_{\mathrm{com}} = 0{,}22\ \mu\mathrm{m}$$

D.3 Student's *t* distribution

Values of t for specified confidence level, as a function of the number of measurements n are given in Table D.1.

Table D.1 – Values of t for specified confidence level

Measurement number	**Confidence level**		
n	**68,3 %**	**95,5 %**	**99,7 %**
2	1,84	14,0	–
3	1,32	4,53	–
4	1,20	3,31	9,22
5	1,14	2,87	6,62
6	1,11	2,65	5,51
7	1,09	2,52	4,90
8	1,08	2,43	4,53
9	1,07	2,37	4,28
10	1,06	2,32	4,09
11	1,05	2,28	3,96
12	1,05	2,25	3,85
13	1,04	2,23	3,76
14	1,04	2,21	3,69
15	1,04	2,20	3,64
16	1,03	2,18	3,59
17	1,03	2,17	3,54
18	1,03	2,16	3,51
19	1,03	2,15	3,48
20	1,03	2,14	3,45
∞	1	2	3

The coverage factor k_i for the particular number of measurements and confidence levels required is given by:

$$k_\mathrm{i} = t \tag{D.3}$$

Annex E
(informative)

Worked examples for the determination of uncertainties

E.1 General

Annex E contains worked examples for the determination of uncertainties in scaling factor, offset factor, fibre measurement and chromium mask measurement. A confidence level of 68,3 % is assumed throughout.

E.2 Example of determination of scaling factor uncertainty

Refer to 6.2.2 and Annex D.

Let

$D_{\mathrm{P,C}}$ = 125,60 µm (calibrated value of parent standard)
$u_{\mathrm{P,C}}$ = 0,07 µm (calibration uncertainty of parent standard)
$D'_{\mathrm{P,C}}$ = 125,15 (measured value of parent standard, raw data)
$u'_{\mathrm{P,C}}$ = 0,05 (statistical uncertainty of measurement, raw data)
n_{C} = 10 (number of measurements)

From Annex D: $t = 1{,}06$

Corrected uncertainty: $u'_{\mathrm{P,C}} = 0{,}05 \times 1{,}06 = 0{,}053$

In this example, let the change in temperature equal 10 °C, and let the dependence of parent standard on temperature equal 0,001 µm/°C.

Thus, from Equation (A.5): $u_{\mathrm{Tr,P,C}} = \dfrac{10 \times 0{,}001}{\sqrt{3}} = 0{,}006\ \mu\mathrm{m}$

From Equation (7): $S = \dfrac{125{,}60}{125{,}15} = 1{,}003\,6$

Then, from Equation (8), the uncertainty in scaling factor is: $u_{\mathrm{s}} = 5{,}8 \times 10^{-4}$

E.3 Example of determination of correction offset uncertainty

Refer to 6.2.3 and Annex D.

Let

$u_{\mathrm{P,F}}$ = 0,05 µm (calibration uncertainty of parent fibre standard)
$u'_{\mathrm{P,F}}$ = 0,05 (statistical uncertainty of measurement, raw data
n_{F} = 10 (number of measurements)
S = scaling factor = 1,003 6 (from E.2)

From Annex D: $t = 1{,}06$

Corrected uncertainty: $u'_{\mathrm{P,C}} = 0{,}05 \times 1{,}06 = 0{,}053$

In this example, let the estimated effect on measurement due to cleanliness of the calibration fibre equal 0,02 µm. Thus $u_{\mathrm{Tr,P,F}}$ = 0,02 µm.

Then, from Equation (11), the uncertainty in offset factor is: u_{O} = 0,06 µm.

E.4 Example of determination of fibre measurement uncertainty

Refer to 6.3 and Annex D.

Let

$D'_{\mathrm{I,F}}$ = 124,50 (measured value of infant fibre, raw data)

$D'_{\mathrm{P,F}}$ = 125,64 µm (diameter of fibre used in offset calibration, see Annex C)

$u'_{\mathrm{I,F}}$ = 0,05 (statistical uncertainty of measurement, raw data)

n_{F} = 10 (number of measurements)

S = scaling factor = 1,0036 (from Clause E.2)

u_{S} = scaling factor uncertainty = $5{,}8 \times 10^{-4}$ (from Clause E.2)

u_{O} = offset factor uncertainty = 0,06 µm (from Clause E.3)

From Annex D: t = 1,06

Corrected uncertainty: $u'_{\mathrm{I,F}} = 0{,}05 \times 1{,}06 = 0{,}053$

In this example, let the estimated effect on measurement due to cleanliness and type of cleave damage present equal 0,02 µm. Thus $u_{\mathrm{Op,I,F}}$ = 0,02 µm.

Then, from Equation (14), the uncertainty in fibre measurement is: $u_{\mathrm{I,F}}$ = 0,07 µm.

E.5 Example of determination of chromium mask measurement uncertainty

Refer to 6.4 and Annex D.

Let

$D'_{\mathrm{I,C}}$ = 125,40 (measured value of infant chromium mask, raw data)

$u'_{\mathrm{I,C}}$ = 0,05 (statistical uncertainty of measurement, raw data)

n_{C} = 10 (number of measurements)

S = scaling factor = 1,0036 (from Clause E.2)

u_{S} = scaling factor uncertainty = $5{,}8 \times 10^{-4}$ (from Clause E.2)

From Annex D: t = 1,06

Corrected uncertainty: $u'_{\mathrm{I,C}} = 0{,}05 \times 1{,}06 = 0{,}053$

In this example, let the estimated effect on measurement due to cleanliness equal 0,007 µm.

Thus $u_{\mathrm{Op,I,C}}$ = 0,007 µm.

Then, from Equation (16), the uncertainty in mask measurement is: $u_{\mathrm{I,C}}$ = 0,08 µm.

Annex F
(informative)

Generation of working standards

F.1 Generation of working standards

F.1.1 General

A working standard for calibration checking is either a fibre or a chromium-on-glass pattern. A working standard is generated by measuring an artefact on a calibrated test set.

F.1.2 Measurement conditions

In order to minimize uncertainties when creating a new working standard, use measurement conditions as similar as possible to those used when the test set was calibrated. The following list details such measurement conditions:

a) in the case of a fibre, the same category of fibre shall be used. In the case of a chromium-on-glass artefact, a similar form is essential (for example an array of dots or lines, a circle or an annulus);

b) the form-fitting algorithms shall be the same;

c) when all the available data from the camera are not used for form-fitting, for example when noise filtering is applied, use the same data selection process;

d) the focusing algorithms shall be the same;

e) the illumination conditions shall be the same;

f) the same edge-setting criterion shall be used.

F.2 Procedure for generation of working standards

F.2.1 In the case where the infant artefact is a fibre

a) Present the infant artefact to the calibrated test set and measure its geometrical parameters using the calibrated scaling factor (see 5.3.4.2). Apply the correction offset factor (see 5.3.4.3) to the measured result. Repeat the measurement as often as necessary to reduce statistical uncertainties.

b) Report the following measurement conditions and measured parameters:
   1) mean diameter and non-circularity;
   2) form-fitting algorithm used;
   3) uncertainty in measurement (see 6.3 for a description of the evaluation of uncertainty).

F.2.2 In the case where the infant artefact is a chromium-on-glass artefact

a) Present the infant artefact to the calibrated test set and measure its geometrical parameters using the calibrated scaling factor (see 5.3.4.2). Do not apply the correction offset factor (see 5.3.4.3) to the measured result. Repeat the measurement as often as necessary to reduce statistical uncertainties.

b) Report the following measurement conditions and measured parameters:
   1) spacing of graduations along the x and y axes;
   2) any form-fitting algorithms used;
   3) uncertainty in measurement (see 6.4 for a description of the evaluation of uncertainty).

Annex G
(informative)

Estimation of uncertainty in the measurement of core/cladding concentricity error

G.1 Method of estimating uncertainty in concentricity error measurement

G.1.1 General

The uncertainty in concentricity error measurement will depend, for example, on the following factors.

a) spatial uniformity of the test set;

b) uncertainty in the determination of the core and cladding centres. This is dependent on the method of curve fitting used, on the number of data points available, and also on the cleanliness and cleave quality of the fibre end;

c) presence of a concentricity bias which may be due to distortions in the optical imaging or illumination systems.

To estimate the uncertainty in concentricity error measurement, the following terms are used:

C	measured concentricity error
u	statistical uncertainty in measurement
n	number of measurements performed
CB	concentricity bias
u_{CB}	uncertainty in concentricity bias
u_{OP}	uncertainty due to fibre effects

The uncertainty u_{C} in concentricity error is given by:

$$u_{\text{C}} = \sqrt{(u_{\text{OP}}^2 + u^2/n + u_{\text{CB}}^2)} + CB \qquad \text{(G.1)}$$

G.1.2 Determination of u

Determine the statistical uncertainty in measurement using Equation (A.2).

G.1.3 Determination of u_{OP}

The operational uncertainty is the uncertainty in the determination of the core and cladding centres. For example, the centre of the core light distribution may be influenced by external perturbations to the fibre.

The operational uncertainty may be estimated using Equation (A.5).

G.1.4 Determination of CB

G.1.4.1 General

The concentricity bias is defined as the distortion of the linear distance between the centres of the core and cladding. Its effect on the measured value will depend on the orientation of the fibre end. A method for determining concentricity bias will now be described.

An optical fibre of similar cladding diameter to the fibre to be measured on the test set after calibration is required; it should be of similar type, for example multimode graded index, multimode step index or single-mode fibre. The test consists in measuring the concentricity error at three different rotational positions of the fibre. A variation in the measured values indicates the presence of a bias in the test set. The procedure to estimate the concentricity bias is as follows.

a) Position the fibre in the instrument and perform a concentricity error measurement. Both the magnitude and the direction of the concentricity error are required. Note the angular position of the fibre image on the viewing monitor by defining an artefact on the fibre edge such as cleave damage. This registration mark is required to enable a controlled rotation of the fibre to be performed.

b) Rotate the fibre about its axis by approximately 120°, using the registration mark defined in step a). Take care to ensure that the fibre end is not translated across the field of view. Perform a concentricity error measurement.

c) Repeat step b) for a further rotational position.

d) Calculate the co-ordinates (x_i,y_i) of the core centre relative to the cladding centre for each of the three measurements i using the following equations:

$$x_i = C_i \times \cos(i) \qquad \text{(G.2)}$$

$$y_i = C_i \times \sin(i) \qquad \text{(G.3)}$$

where

C_i is the concentricity error of measurement i;

θ_i is the angle of concentricity error of measurement i relative to a reference axis.

e) The concentricity bias CB is equal to the distance between the centre (X_0,Y_0) of the circle circumscribed through the points (x_i,y_i) and the cladding centre. Calculate CB using the following equations:

$$X_0 = \frac{(y_3 - y_1)\times(C_2^2 - C_1^2) - (y_2 - y_1)\times(C_3^2 - C_1^2)}{((x_2 - x_1)\times(y_3 - y_1) - (y_2 - y_1)\times(x_3 - x_1))^2} \qquad \text{(G.4)}$$

$$Y_0 = \frac{C_3^2 - 2\times Xo\times(x_3 - x_1) - C_1^2}{2\times(y_3 - y_1)} \qquad \text{(G.5)}$$

$$CB = \sqrt{(X_0{}^2 + Y_0{}^2)} \qquad \text{(G.6)}$$

G.1.4.2 Example of determination of *CB*

Let the measured values for three angular positions be as shown in Table G.1:

Table G.1 – Measured values for angular positions

Angular position	Measured concentricity	
	Magnitude	Angle
0°	0,198 µm	326°
120°	0,238 µm	239°
240°	0,172 µm	122°

Using Equations (G.2), (G.3), (G.4) and (G.5), the bias is:

$$X_0 = -0{,}018\ \mu\text{m} \qquad Y_0 = -0{,}037\ \mu\text{m}$$

The magnitude of the bias calculated using Equation (G.6) is:

$$CB = 0{,}041\ \mu\text{m}$$

G.1.5 Determination of u_{CB}

The uncertainty in the concentricity bias is determined using the following equation:

$$u_{\text{CB}} = \sqrt{\frac{\sum u_{\text{i}}^2}{3}} \tag{G.7}$$

where u_{i} is the statistical uncertainty in the measured concentricity at each rotational position i.

G.2 Correcting for concentricity bias

Once the concentricity bias has been determined, subsequent measurements may be corrected for bias in the following manner.

a) Calculate the $x_{\text{i}}, y_{\text{i}}$ components of the measured concentricity error using Equations (G.3) and (G.4).

b) Subtract the components of the bias X_0, Y_0 from the measured components $x_{\text{i}}, y_{\text{i}}$.

c) Compute the corrected concentricity value C_cor using the following equation:

$$C\_\text{cor} = \sqrt{(x_{\text{i}} - X_0)^2 + (y_{\text{i}} - Y_0)^2} \tag{G.8}$$

The resulting uncertainty in the concentricity error measurement may be determined using Equation (G.2) where the term CB is subtracted from the result.

Annex H
(informative)

Estimation of uncertainty in the measurement of non-circularity

H.1 Method of estimating uncertainty in non-circularity measurement

The uncertainty in the measurement of non-circularity is not dependent on the calibration of the system scaling factor. This is because non-circularity is expressed as a ratio (see 5.6). Some factors affecting uncertainty are given below.

a) The determination of the core or cladding centres, depending on which is being measured, is dependent on the method of curve fitting used, on the number of data points available, and also on the cleanliness and cleave quality of the fibre end.

b) In the case of a fibre core measurement, the non-circularity of the core image may be sensitive to the layout of the fibre.

c) The presence of a non-circularity bias, which may be due to distortions in the optical imaging or illumination systems.

To estimate the uncertainty in non-circularity measurement, the following terms are used:

u	statistical uncertainty in measurement
n	number of measurements performed
NCB	non-circularity bias
u_{NCB}	uncertainty in non-circularity bias
u_{Op}	uncertainty due to cleave effects

The uncertainty u_{NC} in non-circularity is given by:

$$u_{\mathrm{NC}} = \sqrt{(u_{\mathrm{Op}}^2 + u^2/n + u_{\mathrm{NCB}}^2)} + NCB \tag{H.1}$$

H.2 Determination of u

Determine the statistical uncertainty in measurement using Equation (A.2).

H.3 Determination of u_{Op}

The operational uncertainty comprises the uncertainty in the determination of non-circularity due to the effects of cleave damage.

The operational uncertainty may be estimated using Equation (A.5).

H.4 Determination of NCB

H.4.1 General

The non-circularity bias is defined as the distortion of the fibre shape by the imaging system. Its effect on the measured value will depend on the orientation of the fibre end. Two alternative methods to estimate non-circularity are now given.

H.4.2 Method A: uncalibrated artefact

An optical fibre or a chromium-on-glass annulus or circle is required, the diameter of which should be within 5 µm of the diameter of the fibre to be measured on the test set after calibration. The test consists in measuring the non-circularity of the artefact at several rotational positions. A typical angular spacing is 60°. A variation in the measured values indicates the presence of a bias in the test set.

The non-circularity bias is approximated by one half of the range of non-circularity values measured according to the following equation:

$$NCB = \frac{(NC_{\mathrm{max}} - NC_{\mathrm{min}})}{2} \tag{H.2}$$

where NC_{max} and NC_{min} are the maximum and minimum values of non-circularity, respectively.

H.4.3 Method B: calibrated artefact

If the non-circularity of the artefact used is specified as less than a calibrated value u_{cal}, the non-circularity bias may be measured directly. Perform a non-circularity measurement NC on the artefact at an arbitrary orientation. The non-circularity bias is then given by:

$$NCB \leq NC + u_{\mathrm{cal}} \tag{H.3}$$

NOTE The value of NCB determined using method B is the maximum value of the bias in the test set and can be slightly larger than that obtained using method A.

H.5 Determination of u_{NCB}

a) If method A in H.1.4.2 is used, the uncertainty in the non-circularity bias is estimated using the following equation:

$$u_{\mathrm{NCB}} = \frac{u}{\sqrt{2}} \tag{H.4}$$

where u is the statistical uncertainty in the measurement of non-circularity.

b) If method B in H.1.4.3 is used, the uncertainty in the non-circularity bias is estimated using the following equation:

$$u_{\mathrm{NCB}} = u + u_{\mathrm{cal}} \tag{H.5}$$

Bibliography

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