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Optics and photonics — Measurement of optical elements and optical systems —

Part 4:
Interpretation and evaluation of surface form and wavefront deformation tolerances specified in ISO 10110

Optique et photonique — Mesurage de composants et systèmes optiques —

Partie 4: Interprétation et évaluation des tolérances de forme de surface et de déformation du front d'onde spécifiées dans l'ISO 10110

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ISO copyright office
CP 401 • Ch. de Blandonnet 8
CH-1214 Vernier, Geneva
Phone: +41 22 749 01 11
Email: copyright@iso.org
Website: www.iso.org

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Foreword

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This document was prepared by ISO/TC 172, *Optics and photonics*, Subcommittee SC 1, *Fundamental standards*.

This third edition cancels and replaces the second edition (ISO 14999-4:2015), which has been technically revised.

The main changes are as follows:

- The limitation to interferometric measurements techniques only was removed in the title and in the document. The standard explicitly applies also for results of other measurement techniques. Notes were added at locations where differences between interferometric and other measurement techniques have to be accounted for.
- Notes were added regarding alignment removal functions, the wavefront spherical approximation, and the irregularity.
- For the slope deviation specification, a circular test area was added.
- The Zernike residual RMS specification was added, along with the required function and value definitions.
- Calculations of slope deviation where added.
- Definition of curvature deviation was added.
- Annex regarding estimation of peak to valley values was added.
- Some notes were moved in Clause 3 to an appropriate position in the body of the text.

A list of all parts in the ISO 14999 series can be found on the ISO website.

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

Introduction

This document provides a theoretical frame upon which are based indications from ISO 10110-5 and/or ISO 10110-14.

A table listing the corresponding nomenclature, functions, and values used in ISO 10110-5 and ISO 14999-4 is given in ISO 10110-5:2026, Annex B.

ISO 10110-5 refers to deformations in the form of an optical surface and provides a means for specifying tolerances for certain types of surface deformations in terms of “nanometres”.

ISO 10110-14 refers to deformations of a wavefront transmitted once through an optical system and provides a means of specifying similar deformation types in terms of nanometres or optical “wavelengths”.

As it is common practice to measure the surface form deviation interferometrically as the wavefront deformation caused by a single reflection from the optical surface at normal (90° to surface) incidence, it is possible to describe a single definition of interferometric data reduction that can be used in both cases. One “fringe spacing” (as defined in ISO 10110-5) is equal to a surface deformation that causes a deformation of the reflected wavefront of one wavelength.

Certain scaling factors apply depending on the type of interferometric arrangement, e.g. whether the test object is being measured in single pass or double pass.

Due to the potential for confusion and misinterpretation, units of nanometres rather than units of “fringe spacings” or “wavelengths” are to be used for the value of surface form deviation or the value of wavefront deformation, where possible. Where “fringe spacings” or “waves” are used as units, the wavelength is also to be specified.

In the last years several measurement techniques other than interferometric ones have been established that allow measurement of surface form deviations of optical elements and wavefront deformations. These techniques include tactile measurements of optical surfaces, combinations of coordinate measurements machines with optical sensors, and wavefront measurements techniques based on the Shack-Hartmann principle or lateral shearing interferometry. These techniques can be used to obtain the measurement data needed to describe the surface form deviation or wavefront deformations. The calculation rules described in this standard apply to these data sources as well.

Optics and photonics — Measurement of optical elements and optical systems —

Part 4:
Interpretation and evaluation of surface form and wavefront deformation tolerances specified in ISO 10110

1 Scope

This document applies to the interpretation of data relating to the measurement of the surface form deviations of optical elements or the wavefront deformations of optical systems. Often the measurement data are generated by using interferometric techniques, but other measurement techniques also generate measurement data to describe the surface form deviations or wavefront deformations.

This document gives definitions of the optical functions and values specified in the preparation of drawings for optical elements and systems, made in accordance with ISO 10110-5 and/or ISO 10110-14 for which the corresponding nomenclature, functions, and values are listed in ISO 10110-5:2026, Annex B.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 10110-5, *Optics and photonics — Preparation of drawings for optical elements and systems — Part 5: Surface form tolerances*

ISO 10110-14, *Optics and photonics — Preparation of drawings for optical elements and systems — Part 14: Wavefront deformation tolerance*

ISO/TR 14999-2, *Optics and photonics — Interferometric measurement of optical elements and optical systems — Part 2: Measurement and evaluation techniques*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

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

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

3.1 Mathematical definitions

3.1.1
function

f

mathematical description of the measured wavefront deformation or surface form deviation and its decomposition into components

Note 1 to entry: The functions used in this document are scalar functions.

3.1.2
peak-to-valley value

PV(f)

<of a function *f*> maximum value of the function within the region of interest minus the minimum value of the function within the region of interest

Note 1 to entry: The maximum – minimum values of a “real” measurement (that includes measurement artifacts and noise) can significantly overestimate the “true” PV of the underlying function. See Annex A for how PV values shall be processed.

3.1.3
root-mean-square value

rms(f)

<of a function *f* over a given area *A*> value given by either of the following integral expressions:

a) Cartesian variables *x* and *y*

$$\mathrm{rms}(f)=\left[\frac{\int\limits_x\int\limits_y\left[f(x,y)\right]^2\,\mathrm{d}x\,\mathrm{d}y}{\int\limits_x\int\limits_y\mathrm{d}x\,\mathrm{d}y}\right]^{1/2}\quad\text{where}\quad(x,y)\in A$$

b) Polar variables *r* and θ

$$\mathrm{rms}(f)=\left[\frac{\int\limits_\theta\int\limits_r\left[f(r,\theta)\right]^2\,r\,\mathrm{d}r\,\mathrm{d}\theta}{\int\limits_\theta\int\limits_r r\,\mathrm{d}r\,\mathrm{d}\theta}\right]^{1/2}\quad\text{where}\quad(r,\theta)\in A$$

Note 1 to entry: This integral may be approximated by the standard deviation if the usage includes removal of the mean value of the wavefront (piston) and provided that the measurement resolution is specified and is sufficient.

3.1.4
maximum value

max(f)

<of a function *f*> maximum value of the function within the region of interest

Note 1 to entry: The maximum values of a “real” measurement (that includes measurement artifacts and noise) can significantly overestimate the “true” max of the underlying function. See Annex A for details and recommended alternative computations for estimating the max.

3.2 Definition of optical functions

NOTE 1 For the relationship of interferometric measurements to surface form deviation and transmitted wavefront deformation, see Clause 4.

NOTE 2 The optical functions given in this subclause are used either for rotationally invariant (spherical or aspherical) wavefronts (depicted in Figure 1) or cylindrical wavefronts (depicted in Figure 2). The functions describing corresponding features are grouped together; the functions for rotationally invariant wavefronts first and the functions for cylindrical wavefronts follow.

NOTE 3 The term cylindrical waveform is used here as synonym for circular cylindrical, non-circular cylindrical, wavefronts. The functions can also be applied for general wavefronts that are close to cylindrical or toric ones.

NOTE 4 The functions tilt f_{TLT} and twist f_{TWST} are used as alignment removal functions that allow measurements without the need to align the sample under test until these functions are negligible. When measuring general surfaces these functions are not sufficient to describe the effects of misalignments in the measurement setup. The alignment removal functions become shape and device dependent. Therefore, for general surfaces the applicable alignment removal functions are typically defined in a test procedure. The calculation procedures given for specification values in this standard can be used after applying these alignment removal functions.

3.2.1
measured wavefront deformation

f_{MWD}

<wavefront measurements> function representing the distances between the measured wavefront and the nominal theoretical wavefront, measured normal to the nominal theoretical wavefront

Note 1 to entry: See Figure 1 a) and Figure 2 a).

Note 2 to entry: This function can be obtained by several measurement techniques. The interpretation of this function is based on the interferometric measurement approach. That's why it is measured nominal to the theoretical wavefront or surface. The function describes the distance between the measured wavefront and the theoretical wavefront (3.2.1), or the distance between the real surface and the theoretical surface (3.2.2), not the surface itself.

3.2.2
measured surface form deviation

f_{MSD}

<surface measurements> function representing the distances between the measured surface and the nominal theoretical surface, measured normal to the nominal theoretical surface

Note 1 to entry: Use of f_{MWD} or f_{MSD} strictly depends on the context of measurement. For convenience, the function is only referenced as measured wavefront deformation f_{MWD} in the following parts of the document.

3.2.3
tilt

f_{TLT}

plane function representing the best (in the sense of the rms fit) linear approximation to the measured wavefront deformation f_{MWD}

Note 1 to entry: See Figure 1 b) and Figure 2 b).

Note 2 to entry: PV(f_{TLT}) can be a useful measure for parallelism or boresight error in measurements of flat plates or afocal systems.

3.2.4
twist-function describing rotational misalignment for cylindrical wavefronts

f_{TWST}

function of the saddle form used for eliminating rotational misalignment

$$f_{\mathrm{TWST}}(x,y) = \mathrm{const.} \cdot x \cdot y$$

Note 1 to entry: See Figure 2 c).

Note 2 to entry: A rotational misalignment (twist) of the cylindrical axes of the test wave and the surface (respectively, the object under test and the optics generating or compensating the cylindrical or toric phase front) results in an additive term in the form of a saddle. This term could be eliminated or minimized by careful alignment of the setup. In most practical cases, it is more useful to eliminate this term by removing it mathematically.

3.2.5
wavefront deformation

f_{WD}

function resulting after subtraction of the tilt f_{TLT} from the measured wavefront deformation f_{MWD}

$$f_{\mathrm{WD}} = f_{\mathrm{MWD}} - f_{\mathrm{TLT}}$$

Note 1 to entry: See Figure 1 c).

Note 2 to entry: rms (f_{WD}) corresponds to the quantity RMSt in ISO 10110-5 and ISO 10110-14.

Note 3 to entry: PV(f_{WD}) corresponds to the quantity of PVt(D) in ISO 10110-5 and ISO 10110-14.

3.2.6
wavefront deformation

$f_{\mathrm{WD,CY}}$

<cylindrical wavefronts> function resulting after subtraction of the tilt f_{TLT} and f_{TWST} from the measured wavefront deformation, f_{MWD}

$$f_{\mathrm{WD,CY}}(x,y) = f_{\mathrm{MWD}}(x,y) - f_{\mathrm{TLT}}(x,y) - f_{\mathrm{TWST}}(x,y)$$

Note 1 to entry: See Figure 2 d).

Note 2 to entry: rms ($f_{\mathrm{WD,\,CY}}$) corresponds to the quantity RMSt in ISO 10110-5 and ISO 10110-14.

Note 3 to entry: PV($f_{\mathrm{WD,cy}}$) corresponds to the quantity of PVt(D) in ISO 10110-5 and ISO 10110-14.

3.2.7
wavefront spherical approximation

f_{WS}

function of spherical form that best (in the sense of the rms fit) approximates the wavefront deformation f_{WD}

Note 1 to entry: See Figure 1 d).

Note 2 to entry: The technological progress has led to the Numerical Aperture of optical elements increasing beyond the region where the small angle approximation is valid. As a result, the difference between subtracting an exact sphere and the Zernike term $Z(2, 0)$ in the interferogram evaluation in some applications is no longer negligible. For more information see ISO/TR 14999-2:2019, Clause 6.8.

Note 3 to entry: PV(f_{WS}) corresponds to the quantity A in ISO 10110-5 and ISO 10110-14.

Note 4 to entry: Previous versions of this document used the term sagitta deviation to represent this value. For better clarity, the term sagitta deviation has been replaced with power deviation to more accurately reflect the distance normal to a reference surface, whereas sagitta deviation refers to the distance parallel to the z axis to the surface.

3.2.8
wavefront circular cylindrical approximation

$f_{\mathrm{WC,\,x}}$, $f_{\mathrm{WC,\,y}}$

functions of cylindrical form that best (in the sense of the rms fit) approximate the wavefront deformation $f_{\mathrm{WD,CY}}$

$$f_{\mathrm{WC,x}}(x,y) = R_{\mathrm{x,fit}} - \sqrt{R_{\mathrm{x,fit}}{}^2 - x^2} + \mathrm{const.}$$

$$f_{\mathrm{WC,y}}(x,y) = R_{\mathrm{y,fit}} - \sqrt{R_{\mathrm{y,fit}}{}^2 - y^2} + \mathrm{const.}$$

Note 1 to entry: See Figure 2 e) and Figure 2 f).

Note 2 to entry: PV($f_{\mathrm{WC,\,x}}$) corresponds to the quantity AX and PV($f_{\mathrm{WC,\,y}}$) to the quantity AY in ISO 10110-5 and ISO 10110-14.

3.2.9

wavefront irregularity

f_{WI}

function resulting after subtraction of the wavefront spherical approximation f_{WS} from the wavefront deformation f_{WD}

$$f_{\mathrm{WI}} = f_{\mathrm{WD}} - f_{\mathrm{WS}}$$

Note 1 to entry: See Figure 1 e).

Note 2 to entry: PV(f_{WI}) corresponds to the quantity B in ISO 10110-5 and ISO 10110-14.

Note 3 to entry: The PV(f_{WI}) value is extremely sensitive to noise and outliers in the measurement, so use of a trimmed estimator (such as PVr or PV%) is recommended for estimating PV irregularity – see Annex A.

Note 4 to entry: rms(f_{WI}) corresponds to the quantity RMSi in ISO 10110-5 and ISO 10110-14.

3.2.10

wavefront irregularity

$f_{\mathrm{WI,CY}}$

<cylindrical wavefronts> function resulting after subtraction of the wavefront circular cylindrical approximations $f_{\mathrm{WC,x}}$ and $f_{\mathrm{WC,y}}$

$$f_{\mathrm{WI,\,CY}}(x,y) = f_{\mathrm{WD,\,CY}}(x,y) - f_{\mathrm{WC,x}}(x,y) - f_{\mathrm{WC,y}}(x,y)$$

Note 1 to entry: See Figure 2 g).

Note 2 to entry: PV($f_{\mathrm{WI,CY}}$) corresponds to the quantity B in ISO 10110-5 and ISO 10110-14.

Note 3 to entry: rms($f_{\mathrm{WI,CY}}$) corresponds to the quantity RMSi in ISO 10110-5 and ISO 10110-14.

3.2.11

rotationally invariant wavefront approximation

f_{WRI}

rotationally invariant non-spherical function that best (in the sense of the rms fit) approximates the wavefront irregularity, f_{WI}

Note 1 to entry: See Figure 1 f).

Note 2 to entry: In earlier versions of this document this function was named wavefront aspheric approximation.

Note 3 to entry: PV(f_{WRI}) corresponds to the quantity C in ISO 10110-5 and ISO 10110-14.

3.2.12

translationally invariant non-circular cylindrical wavefront approximation

$f_{\mathrm{WTI,x}}$, $f_{\mathrm{WTI,y}}$

translationally invariant non-circular cylindrical function that best (in the sense of the rms fit) approximates the wavefront irregularity for cylindrical wavefronts, $f_{\mathrm{WI,CY}}$ in x and y direction, respectively

$$f_{\mathrm{WTI,x}}(x,y) = f_{\mathrm{WTI,x}}(x)$$

$$f_{\mathrm{WTI,y}}(x,y) = f_{\mathrm{WTI,y}}(y)$$

Note 1 to entry: See Figure 2 h) and Figure 2 i).

Note 2 to entry: PV($f_{\mathrm{WTI,x}}$) corresponds to the quantity CX and PV($f_{\mathrm{WTI,y}}$) to the quantity CY in ISO 10110-5 and ISO 10110-14.

3.2.13
rotationally varying wavefront deviation

f_{WRV}

function resulting after subtraction of the rotationally invariant approximation f_{WRI} from the wavefront irregularity f_{WI}

$$f_{\mathrm{WRV}} = f_{\mathrm{WI}} - f_{\mathrm{WRI}}$$

Note 1 to entry: See Figure 1 g).

Note 2 to entry: rms(f_{WRV}) corresponds to the quantity RMSa in ISO 10110-5 and ISO 10110-14.

3.2.14
translationally varying wavefront deviation

f_{WTV}

function resulting after subtraction of the wavefront non-circular cylindrical approximation $f_{\mathrm{WTI,x}}$ and $f_{\mathrm{WTI,y}}$

$$f_{\mathrm{WTV}} = f_{\mathrm{WI,CY}} - f_{\mathrm{WTI,x}} - f_{\mathrm{WTI,y}}$$

Note 1 to entry: See Figure 2 j).

Note 2 to entry: rms(f_{WTV}) corresponds to the quantity RMSa in ISO 10110-5 and ISO 10110-14.

3.3 Definition of Zernike polynomials

NOTE The Zernike polynomials and their referencing are given in Annex B, originating from ISO/TR 14999-2.

3.4 Definitions of functions and terms for tolerancing the slope and curvature deviation

3.4.1
function after detrending

f_{det}

function resulting after detrending the measured wavefront deformation f_{MWD}, which is used as basis for slope and curvature calculations

Note 1 to entry: The tolerance of the slope deviation describes local surface form deviations. Therefore, a detrending of the function f_{MWD} before calculating the slope deviation can be useful.

3.4.2
local slope deviation for one-dimensional measurements

$\xi_{\text{1-dim}}$

angular deviation of the local normal of the actual (real) surface from the normal of the theoretical surface, measured by means of a one-dimensional measurement with x denoting an arbitrary direction

Note 1 to entry: To calculate the best fit line the following linear equation has to be solved for k in a least square sense, then $\xi_{\text{1-dim}}$ can be calculated from the first component k_1 of k:

$$\begin{pmatrix} x_1 & 1 \\ \vdots & \vdots \\ x_N & 1 \end{pmatrix} \boldsymbol{k} = \begin{pmatrix} f_{\mathrm{det}}\left(x_1\right) \\ \vdots \\ f_{\mathrm{det}}\left(x_N\right) \end{pmatrix}$$

$$\cos\left(\xi_{\text{1-dim}}\right) = \frac{1}{\sqrt{1+k_1^2}}$$

Note 2 to entry: The maximum value of the slope deviation max($\xi_{\text{1-dim}}$) corresponds to the quantity F in ISO 10110-5.

Note 3 to entry: The rms value of the slope deviation rms($\xi_{\text{1-dim}}$) corresponds to the quantity K in ISO 10110-5.