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Geometrical product specifications (GPS) — Surface texture: Areal —

Part 607: Nominal characteristics of non-contact (confocal microscopy) instruments

Spécification géométrique des produits (GPS) — État de surface: Surfacique —

Partie 607: Caractéristiques nominales des instruments sans contact (microscopie confocale)

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ISO copyright office
CP 401 • Ch. de Blandonnet 8
CH-1214 Vernier, Geneva
Phone: +41 22 749 01 11
Fax: +41 22 749 09 47
Email: copyright@iso.org
Website: www.iso.org

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Foreword

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

A list of all parts in the ISO 25178 series can be found on the ISO website.

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

Introduction

This document is a geometrical product specification (GPS) standard and is to be regarded as a general GPS standard (see ISO 14638). It influences the chain link F of the chains of standards on areal surface texture and profile surface texture.

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

For more detailed information of the relation of this document to other standards and the GPS matrix model, see Annex D.

This document describes the metrological characteristics of confocal microscopes designed for the measurement of surface topography maps.

For detailed information on the confocal microscopy technique, see Annex A and Annex B.

NOTE Portions of this document, particularly the informative sections, describe patented systems and methods. This information is provided only to assist users in understanding the operating principles of confocal microscopy. This document is not intended to establish priority for any intellectual property, nor does it imply a license to proprietary technologies described herein.

Geometrical product specifications (GPS) — Surface texture: Areal —

Part 607: Nominal characteristics of non-contact (confocal microscopy) instruments

1 Scope

This document describes the influence quantities and instrument characteristics of confocal microscopy systems for areal measurement of surface topography. Because surface profiles can be extracted from surface topography images, the methods described in this document can be applied to profiling measurements as well.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 25178-600 and the following apply.

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

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
confocal microscopy
measurement method wherein the localization of optically sectioned images during an axial scan through the focus of a microscope's objective provides a means to determine an areal surface topography image

Note 1 to entry: See also ISO 25178-6:2010, 3.3.6.

Note 2 to entry: Confocal microscopes produce optically sectioned images by restricting the illumination onto the sample and through the detection system by means of a pattern, scanning this pattern in-plane to fill the image (see also Figure B.1).

Note 3 to entry: Illumination and detection patterns could be one or several points, slits or any order of structures, that effectively reduce the illuminated area of the surface. The geometry of these patterns influences the evaluation of the sectioned images and has direct influence on the metrological characteristics of the instrument.

Note 4 to entry: The difference between a confocal point sensor and a confocal microscope is defined by the in-plane scanning scheme. In the confocal microscope one or multiple parallel working light paths scan the surface. This is realized with various optical elements. In contrast, the single point confocal probe scans only one point on the sample at a time by moving either the sample or the probe. A single point confocal chromatic probe arrangement is described in ISO 25178-602:2010, Annex B.

Note 5 to entry: Table 1 compiles alternative terms that conform at least in part to the above definition.

Table 1 — Examples of alternative terms sometimes used for confocal microscope

Acronym	Term
ICM	imaging confocal microscope
LSCM	laser-scanning[a] confocal microscope (see also A.2)
CLSM	confocal laser-scanning[a] microscope (same method as LSCM)
CSLM	confocal-scanning laser microscope (same method as LSCM)
LSM	laser-scanning[a] microscope (same method as LSCM)
DSCM	disc-scanning confocal microscope (see also A.3)
PACM or PAM	programmable array confocal microscope or programmable array microscope (see also A.4)
MSCM	microdisplay scanning confocal microscope (same method as PACM)
RSOM	real-time scanning optical microscope
CSOM	confocal-scanning optical microscope

[a] The term 'laser-scanning microscope' has also been used to refer to laser-based scanning probes with height sensors, such as triangulation or dynamic focus, which are different from the confocal methods described here.

3.2
illumination pattern
arrangement of single or repetitive structures placed on a conjugate image position of the microscope's objective (typically the field diaphragm position), restricting the illuminated parts on the sample

Note 1 to entry: The illumination pattern can be a single pinhole, equally spaced pinholes on a grid, slits, parallel slits or any other pattern that effectively reduces the amount of illuminated area.

3.3
detection pattern
arrangement of single or repetitive structures placed on a conjugate image position of the microscope's objective, blocking the out-of-focus light reflected from the surface and from previously illuminated parts

Note 1 to entry: The illumination and detection patterns need not have the same geometry.

3.4
in-plane scanning
mechanical or optical displacement of the illumination and/or detection patterns to fulfil an optical section image

Note 1 to entry: Annex A describes the principle of in-plane scanning for typical confocal arrangements.

3.5
axial scan
mechanical or optical displacement between the sample under inspection and the imaging optics

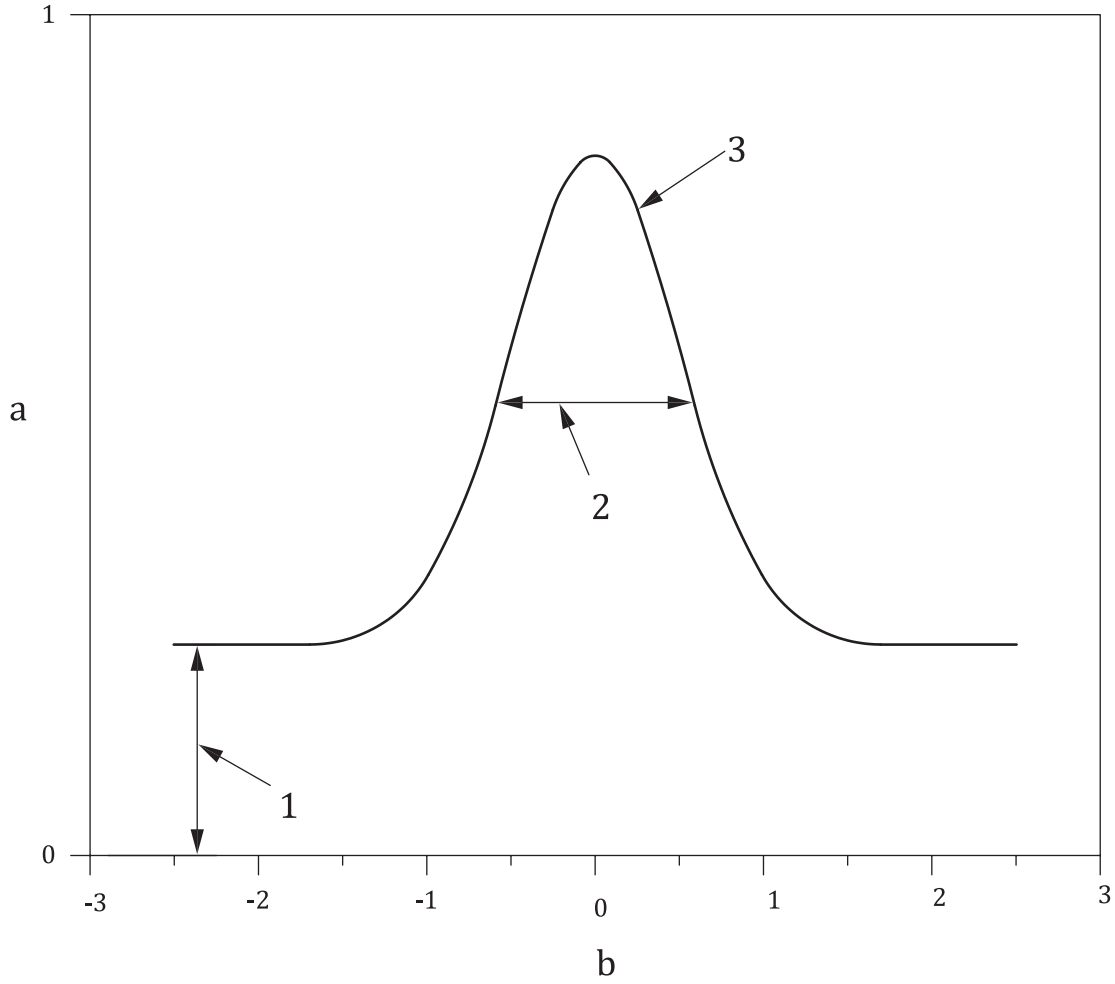
Note 1 to entry: The imaging optics is nominally parallel to the axial scan axis of the microscope.

3.6
axial scan length
total range travelled by the confocal microscope axial scan, usually the total displacement between the sample and the microscope's objective translated along its optical axis during data acquisition

Note 1 to entry: This parameter might be limited by the overall range of the axial scanner, but is generally a parameter chosen by the operator taking account of the height range of the surface topography.

3.7
axial response
signal recorded for an individual image point of the confocal image as a function of the axial scan position

Note 1 to entry: See Figure 1.



Key

a normalized detector signal
b *z*-height
1 background offset
2 full width at half maximum
3 axial response

Figure 1 — Schematic axial response signal

3.8
full width at half maximum
FWHM
$\Delta_{z\text{-}HM}$
region of the axial response symmetrical to the maximum peak where the signal falls to one-half of the maximum peak signal

Note 1 to entry: The FWHM is used as a metric (or estimator) of the thickness of the optically sectioned slice.

3.9
maximum signal position
position of the axial scan where the amplitude of the axial response is maximum

3.10
background offset
value of the axial response for axial positions far from the maximum signal position

Note 1 to entry: The background offset might be caused by residual reflected and scattered light within the instrument and from the sample, "cross talking" between pinholes and incomplete sectioning behaviour of the light path.

Note 2 to entry: Methods exist which reduce or make use of background offset effects.

3.11
axial steps
distance between two consecutive confocal images during an axial scan

3.12
confocal imaging rate
number of confocal images per second provided by a confocal microscope without axial scan

3.13
axial scanning rate
number of confocal images per second provided by a confocal microscope during an axial scan, expressed as the number of acquired plane sections per second

Note 1 to entry: The axial scanning rate might be equal to or lower than the confocal imaging rate depending on the scanning hardware used and the processing algorithms.

3.14
flatness calibration surface
reference surface used to measure and adjust for the microscope flatness error

Note 1 to entry: The calibration surface is typically an optically flat single surface mirror (flatness ≤ $\lambda/10$ and roughness average R_a < 0,5 nm).

3.15
confocal peak location algorithm
algorithm used to estimate the maximum signal position of the surface point from the axial response

Note 1 to entry: The maximum signal (confocal peak) position is equated to the axial location of the surface.

Note 2 to entry: The confocal peak is not necessarily represented by the absolute maximum of the axial response; there are multiple algorithms (see Annex B).

3.16
maximum measurable local slope
<confocal microscopy> largest slope that can be measured on an optically smooth surface

Note 1 to entry: See ISO 25178-600:2019, Annex A.

3.17
confocal stack
series of optical sections taken during an axial scan

3.18
confocal topography image
areal topography image derived from a stack of optical sections obtained during an axial scan

Note 1 to entry: Generally, for each pixel of the image the *confocal peak location algorithm* (3.15) is applied to the *confocal stack* (3.17) to calculate the height of the surface.

3.19
confocal intensity image
areal intensity image derived from a stack of optical sections obtained during an axial scan

Note 1 to entry: For each pixel of the image an algorithm is applied that finds the reflected intensity of the surface. The applied algorithm might be different from the algorithm (3.15) to find the height of the surface.

Note 2 to entry: Such a group of images typically shows a depth of field close to the axial scan range.

4 Descriptions of the influence quantities

Influence quantities for confocal microscopy instruments are given in Table 2. The table indicates the metrological characteristics (see ISO 25178-600:2019, Table 1) affected by deviations in the influence quantities.

Table 2 — Influence quantities for confocal microscopy

Component	Element	Influence quantities		Metrological characteristic affected
Light source		λ_0	Measurement optical wavelength (see ISO 25178-600)	α_z
		$B_{\lambda 0}$	Measurement optical bandwidth (ISO 25178-600)	α_z
Microscope imaging system		A_N	Microscope numerical aperture (see ISO 25178-600)	α_x, α_y, α_z, W_R
		M_{IMG}	Magnification between object sizes on the surface and image sizes on the sensor	α_x, α_y
		Δ_{PATH}	Optical aberrations – a function describing net deviations in the measured optical path of the system, derived from imperfections in the optics and the topography of the flatness calibration surface	α_z
		Q_{OPT}	General quality of the optical components used, including aberrations, transmission and alignment errors	α_x, α_y, z_{FLT}, l_x, l_y, l_z, W_R, Δ_x, Δ_y
		P_{DISxy}	Lateral distortion of the magnified image on the camera	α_x, α_y, α_z, z_{FLT}, l_x, l_y, l_z, W_R, Δ_x, Δ_y
		$U_{I(x,y)}$	Illumination uniformity – distribution of illumination across the field of view of the object (a highly uniform, constant distribution is desired)	α_x, α_y, α_z, z_{FLT}, l_x, l_y, l_z

[a] These influence quantities arise from the interaction between the instrument and the sample being measured.

Table 2 *(continued)*

Component	Element	Influence quantities		Metrological characteristic affected
Camera		δ_x	x-pixel spacing of the imaging camera	α_x, W_R
		δ_y	y-pixel spacing of the imaging camera	α_y, W_R
Controller	Acquisition software	f_z	Axial scanning rate (3.13)	α_z, l_z
		z_{TOT}	Axial scan length (3.6)	α_z, l_z
		Δ_z	Axial steps (3.11)	α_z
		T_I	Integration time required to complete a single scan in z	N_M
	Profile analysis software	A_{ALG}	Confocal peak location algorithm (see 3.15)	α_z, l_z
Instrument overall		D_x or D_y	Lateral sampling interval – equal to the lateral pixel spacing of the camera (δ_x, δ_y) divided by the magnification (ISO 25178-600)	W_R
		$\Delta_{z\text{-LIN}}$	Scan linearity	α_z, l_z
		N_I	Instrument noise (see ISO 25178-600)	N_M
		N_{VIB}	Environmental vibration – unwanted motion between the surface being measured and the optical system	N_M
Sample		θ_{TLT}[a]	Tilt – relative angle between the optical axis of the system and the local sample normal. Object surface slopes that cause light to reflect near to the edge or outside of the numerical aperture of the objective also likely cause significant signal loss. Therefore, in optical systems the maximum measurable local slope (3.16) is largely determined by the numerical aperture. The issue is illustrated in ISO 25178-600	α_x, α_y, α_z
		n[a]	Complex index of refraction of dissimilar materials	α_z
		T_{FLM}[a]	Thickness of transparent or semi-transparent surface films (see Annex C for more information)	α_z
		F_{UR}[a]	Under-resolved features – object features with lateral dimensions in the order of or smaller than the lateral resolution	α_z

[a] These influence quantities arise from the interaction between the instrument and the sample being measured.

Annex A
(informative)

Classification of in-plane scanning techniques for confocal microscopes

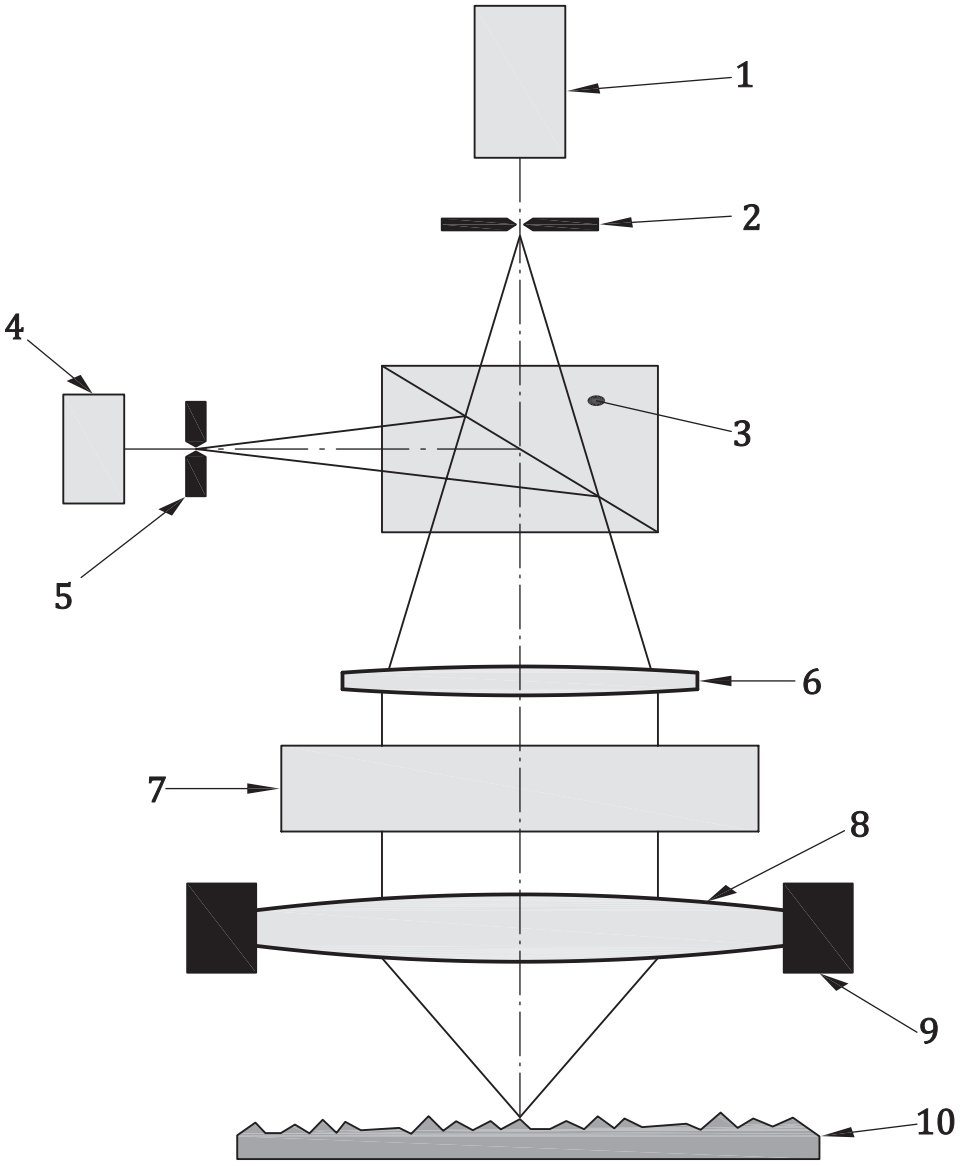
A.1 General

This annex describes some technical principles used for scanning the illumination and detection patterns of a confocal arrangement in the plane perpendicular to the optical axis (x,y plane) to produce an optical section. To recover a topography map of the surface, the in-plane scanning is combined with axial scanning to produce a sequence of optical sections. The axial scanning process is described in Annex B.

A number of different confocal arrangements have been developed. There are different techniques for in-plane scanning, for illumination and detection patterns, and for detector arrangements. Each different configuration optimizes a given application such as maximization of light efficiency, optimization of signal-to-noise ratio, optimization of speed, simplification or reduction of hardware cost, adaptation to different excitation wavelengths and others. Three typical configurations of confocal microscopes are laser scanning, disc scanning and programmable array scanning.

A.2 Laser-scanning confocal microscope (LSCM) configuration

In a laser-scanning confocal microscope the illumination and detection pattern consists of two single pinholes placed on optically conjugate planes. The beam emerging from the illumination pinhole is scanned in a raster fashion across the sample in order to build up a confocal image point by point. Figure A.1 shows the basic configuration of a LSCM. A laser beam illuminates a pinhole. The image of the pinhole is formed on the sample placed on the focal plane of the objective. The light reflected or backscattered from the sample passes back through the objective and is imaged onto a second pinhole called the confocal *aperture* placed on a conjugate position to the illumination pinhole. A detector on the rear of the confocal aperture records the signal reflected from the surface. Light reflected from out-of-focus positions reaches the confocal aperture plane as an out-of-focus image, resulting in a low signal at the detection plane. The beam of the illumination pinhole is scanned in a raster fashion along the x- and y-directions in order to generate a confocal image. Generally, the beam is deflected by two mirrors that rotate in perpendicular directions.



Key

1 laser
2 illumination pinhole
3 beamsplitter
4 detector
5 detection pinhole
6 field lens
7 beam scanning device
8 objective
9 axial scanning device
10 sample

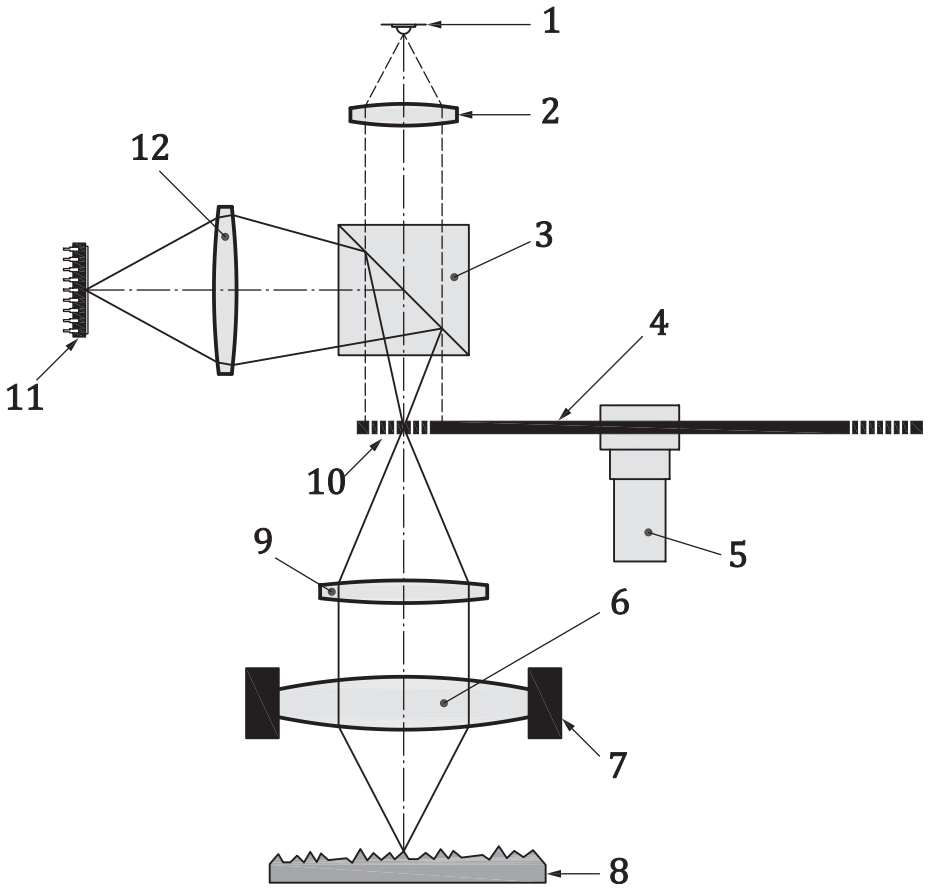
Dash-dotted lines: optical axes

Solid lines: illumination and observation path

Figure A.1 — Typical arrangement of a LSCM

A.3 Disc-scanning confocal microscope (DSCM) configuration

The structure of the pattern for the in-plane scanning can be multiple pinholes or slits. Figure A.2 shows the basic schematic of a disc-scanning confocal microscope, exemplified by a multi-pinhole pattern. A light source is collimated and directed to a multi-pinhole disc. The disc contains a pattern of apertures (Figure A.3) that functions simultaneously as illumination pattern and detection pattern. Each one of the pinholes is imaged onto the surface by means of a field lens and the microscope's objective. The light reflected or backscattered from the surfaces for each illuminated spot passes back through the objective and the field lens and is focused onto the same pinhole of the disc. Light arising from the focal plane is well focused on the disc surface while light from out-of-focus regions is focused onto planes before or after the disc. Each one of the pinholes acts as an illumination and detection element at the same time. Light transmitted through the pinholes is focused onto a two-dimensional light detector, like a CCD camera. The disc is rotated at high speed, illuminating and filtering out-of-focus light sequentially and producing an optically sectioned image.



Key

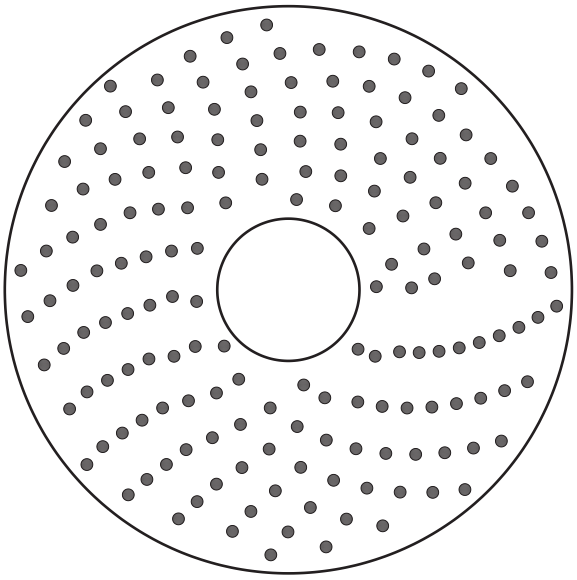
1 light source
2 collimator
3 beamsplitter
4 scanning disc
5 motor
6 objective
7 axial scanning device
8 sample
9 tube lens
10 multi-pinhole-filter
11 detector
12 imaging optics

Dashed lines: illumination beam path

Dash-dotted lines: optical axes

Solid lines: observation beam path

Figure A.2 — Typical arrangement of a DSCM



NOTE Hole sizes and hole densities are not to scale.

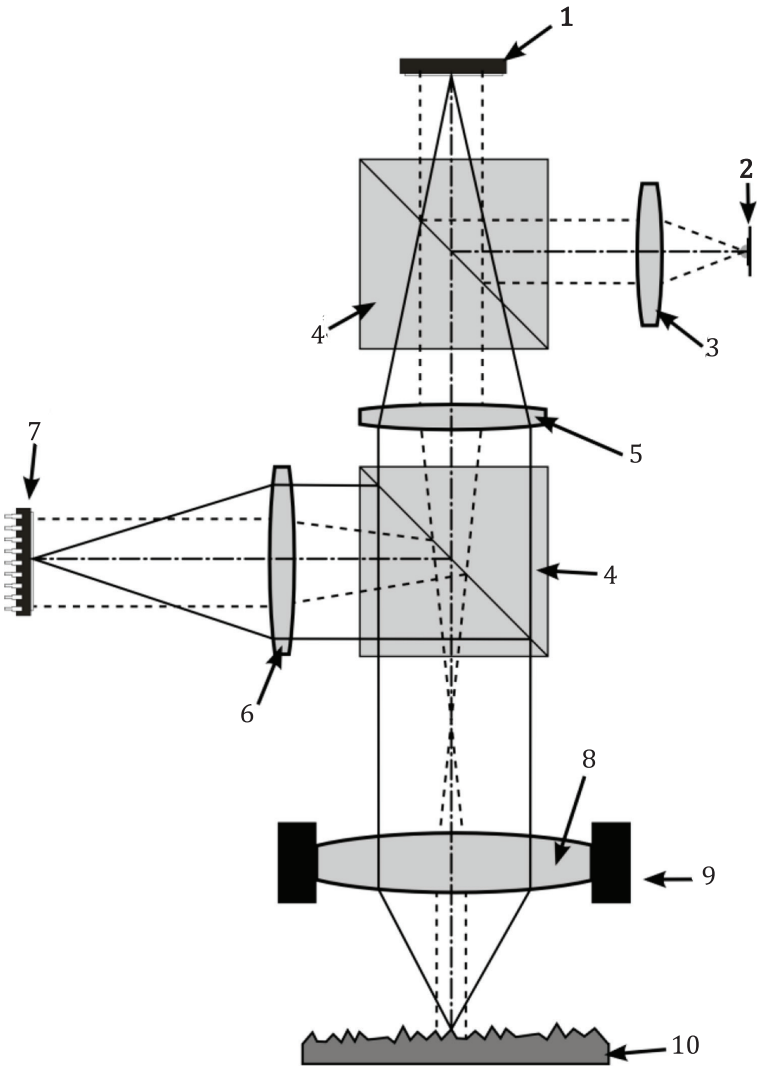
Figure A.3 — Schematic diagram of a multi-pinhole disc in a DSCM

A.4 Programmable array confocal microscope (PACM or PAM) configuration

Programmable array microscopes (PAMs) may be used in confocal arrangements to establish the PACM method. Like disc-scanning microscopes, PAMs use parallel illumination to increase the scanning speed, the signal or both[26]. The active element on a PAM is a microdisplay, such as a digital micro mirror device (DMD), for example placed on the field diaphragm position of the microscope. The microdisplay is used to generate illumination and/or detection patterns[15].

A PAM can be arranged in illumination-only mode or in illumination and detection mode[5]. In illumination-only mode the pixels of the microdisplay are used to restrict the light spots on the surface and the optical sectioning is achieved by the use of the pixels of a CCD camera. In contrast, in illumination and detection mode the pixels of the microdisplay are used to illuminate the surface and at the same time to filter out the light that falls out of focus. Figure A.4 shows a typical configuration of a PAM in illumination-only mode.

A PAM operating in the illumination and detection mode is similar to a DSCM, where the disc is replaced by the microdisplay. Each pixel of the microdisplay acts as both the illumination and the detection element at the same time. PAMs in illumination and detection mode are selected for high-speed imaging, but suffer from low light efficiency. The main benefit of a PAM is the fact that the illumination and detection pattern can be adapted to the surface under inspection. The illumination pattern can be a series of equally spaced elements (acting like pinholes), simulating a multi-pinhole disc, or a series of parallel slits, or any other pattern that effectively confines the amount of illuminated regions.



Key

1 microdisplay or DMD
2 light source
3 collimator
4 beamsplitter
5 field lens
6 imaging optics
7 detector
8 objective
9 axial scanning device
10 sample

Dashed lines: illumination beam path
Dash-dotted lines: optical axes
Solid lines: observation beam path

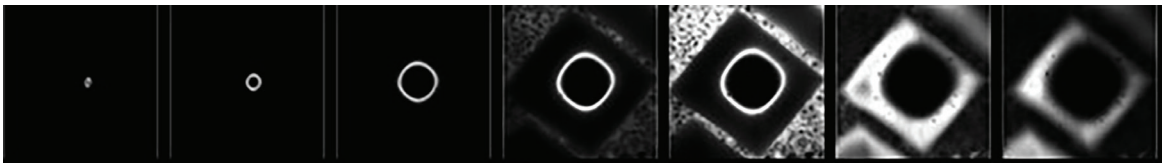
Figure A.4 — Typical arrangement of a PAM with an illumination-only configuration

Annex B
(informative)

Theory of operation of confocal microscopes

B.1 Axial scanning

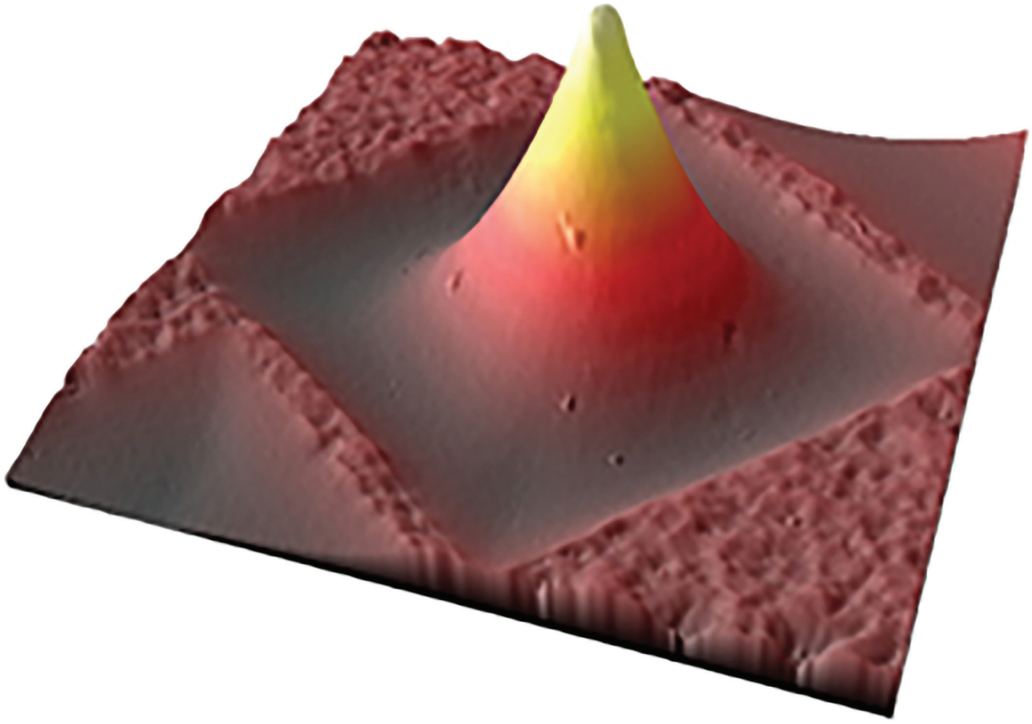
Confocal microscopy[32] combines the capability to produce optically sectioned images with axial scanning to provide three-dimensional confocal topography images. The basic principle of confocal topography measurement relies on storing a sequence of confocal images in the memory of a computer taken from different *z*-planes along the depth of focus of the microscope's objective. A sequence of confocal images is shown in Figure B.1. An optically sectioned image shows bright grey pixel levels for those regions of the surface that lie within the depth of focus of the objective, and dark grey pixel levels for the rest of the parts of the surface that are out of focus.



NOTE The field of view of each image is approximately 100 µm × 100 µm.

Figure B.1 — A series of confocal images through the depth of focus of a confocal microscope's objective

Each pixel of the image contains a signal along the *z*-direction called the axial response, shown in Figure 1. The maximum signal of the axial response is reached when the surface is exactly located on the focal plane of the microscope's objective. Different pixels will have the maximum signal position located at different *z*-positions according to the three-dimensional surface shape. By locating the *z*-position of the maximum of the axial response for each pixel, the three-dimensional confocal topography image is reconstructed. Figure B.2 shows the confocal topography image calculated from the series of images in Figure B.1. Note that confocal microscopes may also be used to produce confocal intensity images (3.19).



NOTE The peak-to-valley height is approximately 5 µm.

Figure B.2 — The three-dimensional surface calculated from the series of images in Figure B.1

B.2 Sequencing in-plane scanning and axial scanning

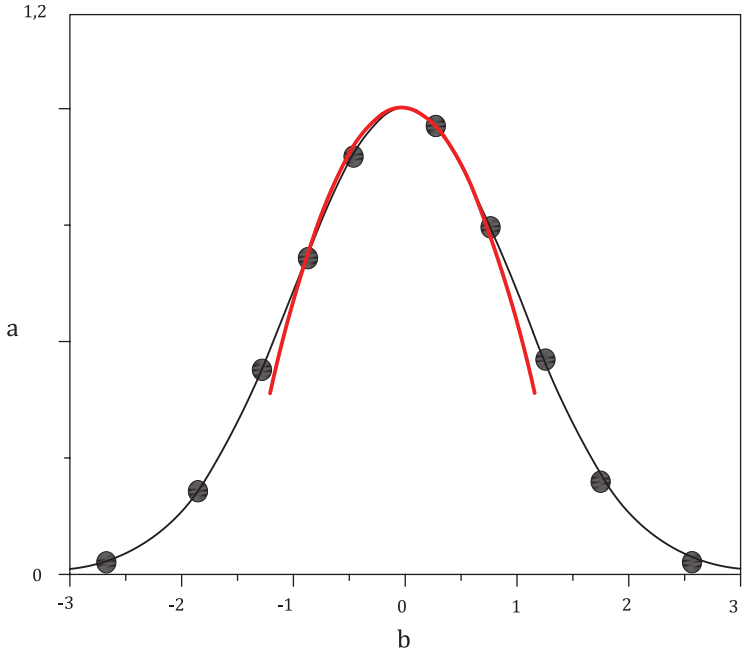
Three types of confocal microscope are described in Annex A. A confocal image is built up by scanning in plane (in the *x*- and/or *y*-direction) an illumination pattern and a detection pattern. For any confocal design, the sample and the focal plane of the microscope's objective should not be moving axially during in-plane scanning. For three-dimensional measurements of surfaces, the in-plane scanning and the axial scanning should not be simultaneous.

B.3 Axial scanner

The axial (vertical) scanner on a confocal microscope determines the *z*-values of the constructed confocal topography image and, therefore, is one of the important components for areal topography measurements. The location in *z* of the maximum of the axial response for each pixel of the image is directly related to the positioning accuracy of the *z*-stage itself. Any nonlinearity of the axial scan will be embedded in the areal surface measurement. Typically, the vertical scanner on a confocal microscope displaces one of the three components: the sample, the objective or the full sensor. Many designs have been implemented to address the accuracy of *z*-axis measurements.

B.4 Confocal peak location algorithms

The *z*-location of the maximum of the axial response nominally indicates the height location of the three-dimensional surface[10]. The fastest way to estimate the surface height is to assign it to the discrete position of the scanner at the maximum signal. Alternatively, more advanced mathematical methods are generally used in order to locate the surface height more accurately. A well-known algorithm is the centre of mass algorithm. Another widely used algorithm is parabolic fitting (Figure B.3) of a few points near the maximum signal position. More advanced algorithms may include, for example, Gaussian[32] or sinc^2 fitting functions[34][35] to the full axial response. Such a procedure is more precise but might require more processing time.



Key

a normalized detector signal

b z (μm)

Figure B.3 — Parabolic fitting to some points around the maximum signal position

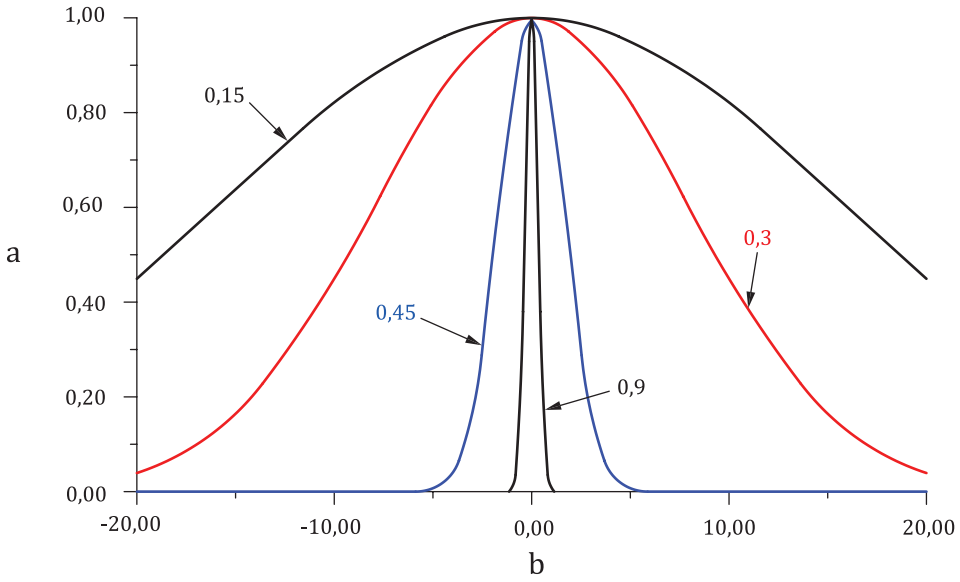
B.5 Resolution vs A_N

Although the metrological algorithm is capable of providing vertical position resolution well below the z-slice interval, the vertical position resolution is also limited by the numerical aperture of the objective. The lower the numerical aperture, the wider the axial response. The optical full width at half maximum (FWHM), $\Delta_{z\text{-HM}}$, of the axial response of a confocal microscope is approximately given by Formula (B.1):

$$\Delta_{z\text{-HM}} = \left(\frac{0{,}88\,\lambda_0}{1-\sqrt{1-A_N{}^2}} \right) \tag{B.1}$$

Figure B.4 shows different axial responses for different numerical apertures.

For objectives with low numerical aperture, the maximum signal position is difficult to locate because the signal decreases slowly. Objectives with high A_N have sharper peaks and allow for more precise location of the maximum. The z-step between planes may be matched to the resolution of the objective. Low magnification objectives have typically low A_N and z-resolution, typically 50 nm or more. For objectives reaching 0,75 A_N or larger, the vertical position resolution approaches 1 nm.



Key

a normalized intensity

b z (µm)

Figure B.4 — Axial response for different numerical apertures A_N (λ_0 = 0,55 µm)

Annex C
(informative)

Thin and thick films with confocal microscopes

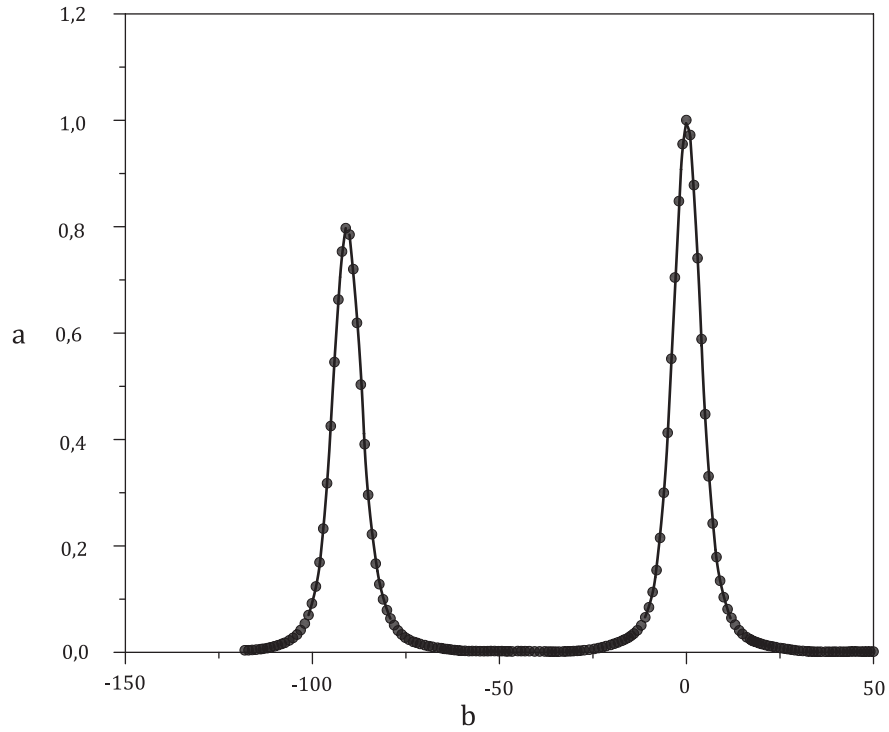
C.1 General

One of the applications, which is considered to be difficult to carry out with optical imaging profilers, is the measurement of stratified media. These media show refractive-index variations in the axial direction. Typical examples are integrated circuit architectures, integrated optics structures and optoelectronic devices.

C.2 Thick films

Axial imaging is obtained in a confocal microscope by scanning the sample through the confocal depth of focus. For a thick film we obtain peaks in the axial response arising from reflection at the two parallel reflecting surfaces. The widths of the peaks are reduced when A_N of the objective increases, and the distance between the peaks increases with the thickness of the film[21]. Figure C.1 shows the experimental axial response for a 140-µm-thick glass sheet (n_1 = 1,52) obtained with a 10×, 0,3 A_N objective.

The measured separation of the peaks h_m is very different from the real thickness h of the sheet because of two important factors: depth distortion due to the index of refraction n of the medium and the spherical aberration caused by focusing with high A_N optics through a refractive medium. The index of refraction in turn depends on several factors. In air for visible light, $n \cong 1$ but has a slight dependence on optical wavelength and on ambient temperature and pressure (see ISO 25178-600).



Key

a normalized detector signal

b z/µm

NOTE The numerical aperture is 0,30 and the peak separation h_m is 90,917 µm.

Figure C.1 — Axial response of a 140-µm-thick glass sheet

C.3 Thin films

When the thickness of the film under inspection is reduced, the two peaks on Figure C.1 get closer and finally overlap. At this point it is said that the film cannot be resolved with a confocal microscope.

Annex D
(informative)

Relation to the GPS matrix model

D.1 General

The ISO GPS matrix model given in ISO 14638 gives an overview of the ISO GPS system of which this document is a part[36].

The fundamental rules of ISO GPS given in ISO 8015 apply to this document and the default decision rules given in ISO 14253-1 apply to specifications made in accordance with this document, unless otherwise indicated.

D.2 Information about this document and its use

This document defines the methods, specific terminology and metrological characteristics for confocal microscopes used to measure areal and profile surface texture.

D.3 Position in the GPS matrix model

This document is a general ISO GPS standard which influences chain link F of the chains of standards on profile and areal surface texture in the GPS matrix model. The rules and principles given in this document apply to all segments of the ISO GPS matrix which are indicated with a filled dot (·).

Table D.1 — Position in the ISO GPS standards matrix model

	Chain links						
	A	**B**	**C**	**D**	**E**	**F**	**G**
	Symbols and indications	Feature requirements	Feature properties	Conformance and non-conformance	Measurement	Measurement equipment	Calibrations
Size							
Distance							
Form							
Orientation							
Location							
Run-out							
Profile surface texture						•	
Areal surface texture						•	
Surface imperfections							

D.4 Related international standards

The related International Standards are those of the chains of standards indicated in Table D.1.

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