

Developing Optical Metrology in the ISO 25178-framework

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Also:



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Editor-in-Chief of "Metrology"



metrology

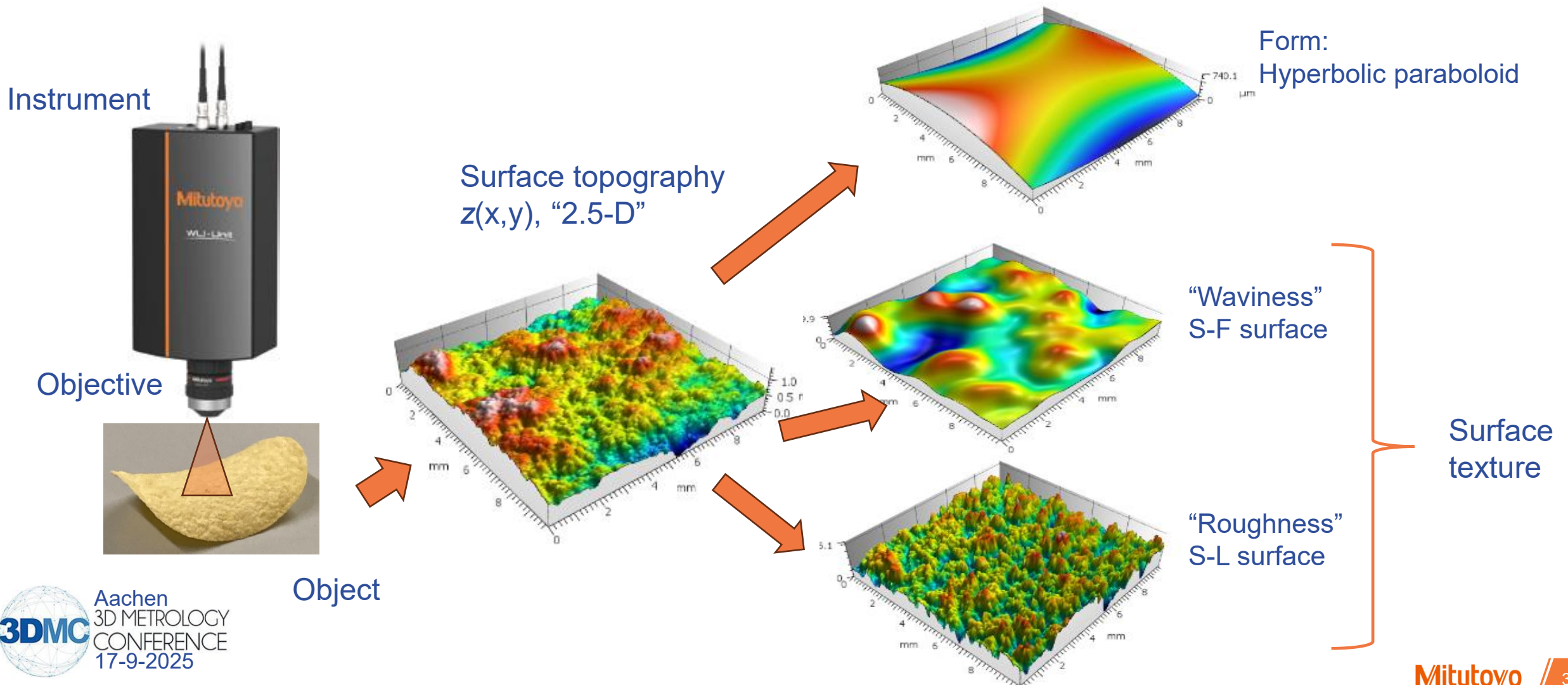
Content

- The ISO 25178 framework
- Metrological characteristics
- Instrument noise and measurement noise
- Flatness deviations
- WLI Objectives: the heart of the system
- A white-light module



The ISO 25178 framework

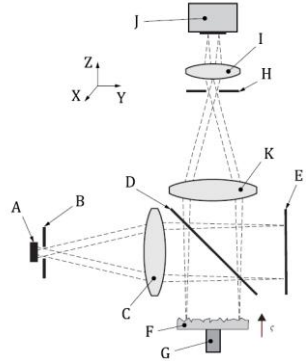
The ISO 25178 series are about: Surface texture: Areal



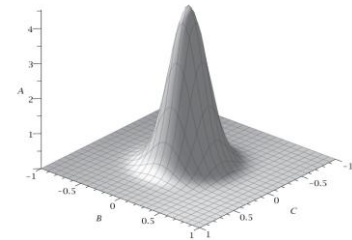
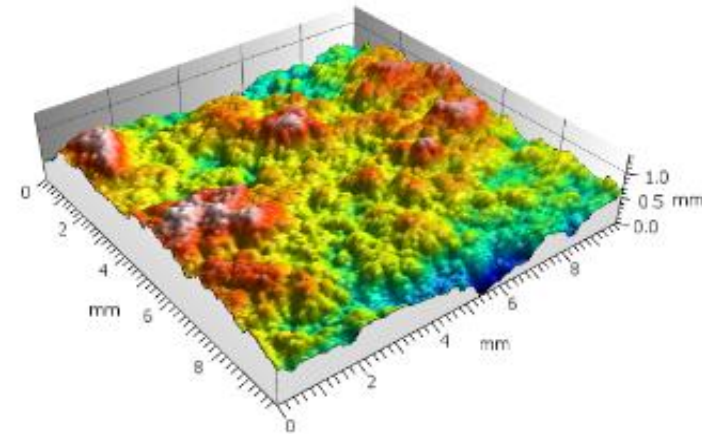
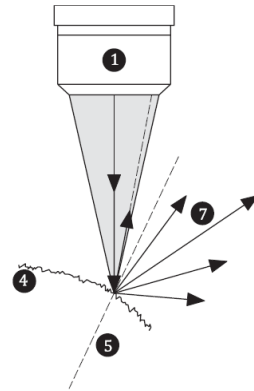
The ISO 25178 framework

The ISO 25178 series are about: Surface texture: Areal

ISO 25178-604
Coherence scanning
interferometry



ISO 25178-600
Metrological characteristics



ISO 25178-1; Indication

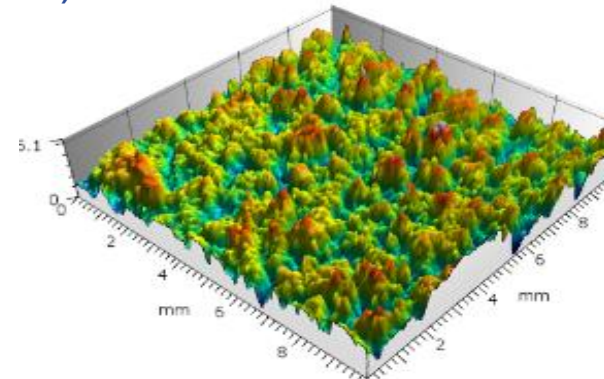
ground and honed X
 $\square / L \text{ S-F } 0,025\text{-RG8/Smr}(5\%,-0,2) \text{ } 60\% / \text{ ES}$

ISO 25178-3; Specification
(Resolution, bandwidth)

ISO 16610-61: Areal Gaussian filter

ISO 25178-2; parameters

$$S_a = \frac{1}{A} \iint_{\tilde{A}} |z(x, y)| dx dy$$



Metrological Characteristics in ISO 25178-60x

2010-2015

- 601: Stylus instruments
- 602: Confocal chromatic probes
- 603: Phase shifting interferometry
- 604: Coherence scanning interferometry
- 605: Point autofocus systems
- 606: Focus variation
- 607: Confocal microscopy

2019

600: Metrological characteristics:
general

Metrological characteristic	Symbol
Amplification coefficient	$\alpha_x, \alpha_y, \alpha_z$
Linearity deviation	l_x, l_y, l_z
Flatness deviation	z_{FLT}
Measurement noise	N_M
Topographic spatial resolution	W_R
x-y mapping deviations (Note 1)	$\Delta_x(x,y), \Delta_y(x,y)$
Topography fidelity	T_{FI}

~2025

All rewritten:

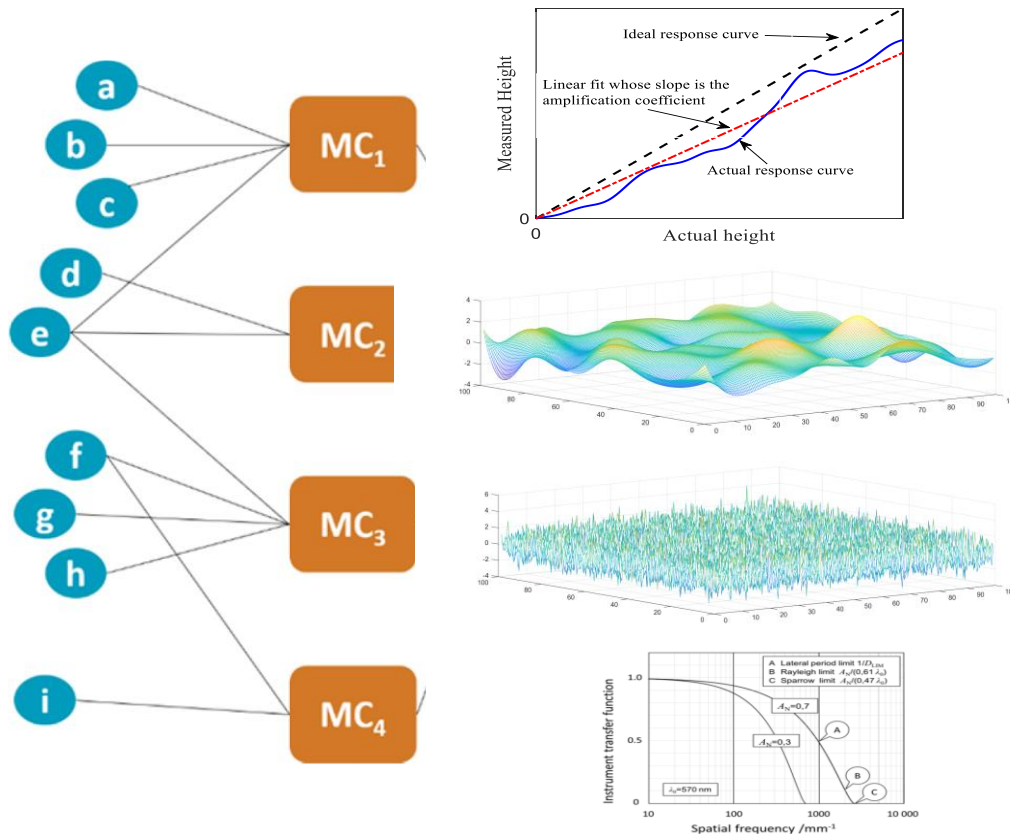
- 601: Stylus instruments
- 602: Confocal chromatic probes
- 603: Phase shifting interferometry
- 604: Coherence scanning interferometry
- 605: Point autofocus systems
- 606: Focus variation
- 607: Confocal microscopy

Metrological Characteristics in ISO 25178-

Background of metrological characteristics

- Common to all measuring instruments
- Influencing factors may be instrument- and specimen-specific

ISO 25178-600 defines Metrological Characteristics
 ISO 25178-700 defines default calibration methods
 ISO 25178-60x gives influencing factors



Linearity

Flatness

Noise

Spatial resolution

Topography

Remove form, filter
 see ISO 16610-xx

Texture

Parameter value
 (e.g. S_q , step height)
 see ISO 25178-2

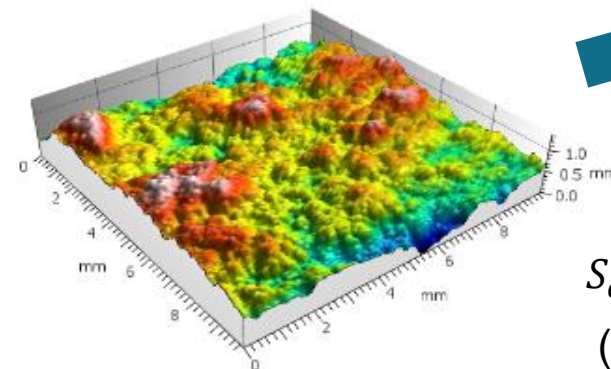
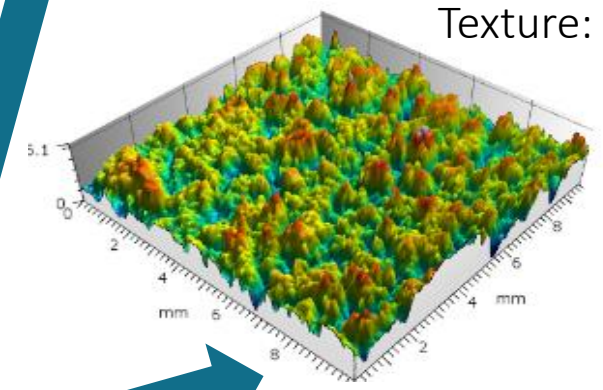
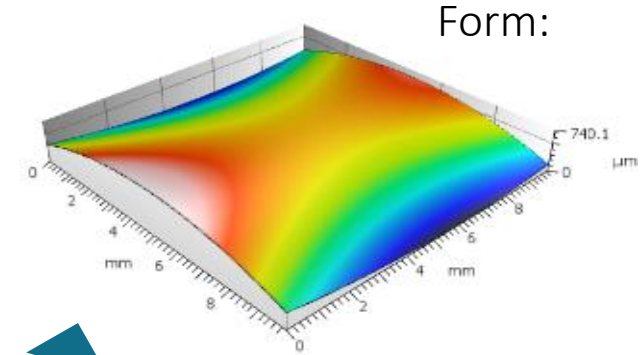
Uncertainty in parameter

a..i: influencing factors (instrument specific) MC_i : **M**etrological **C**haracteristics

Metrological Characteristics in ISO 25178-

Influence quantity
Equivalent wavelength
Mean value of the CSI scan increment
Focus effects
Reference mirror flatness
Optical ray tracing error
Random environmental vibration
Camera noise
Optical lateral resolution
Sampling interval
Optical distortion
Surface films
Dissimilar materials
Surface slopes and discrete step features
CSI scan linearity
Fringe-order errors

Metrological characteristic
Amplification coefficient
Linearity deviation
Flatness deviation
Measurement noise
Topographic spatial resolution
x-y mapping deviations (Note 1)
Topography fidelity

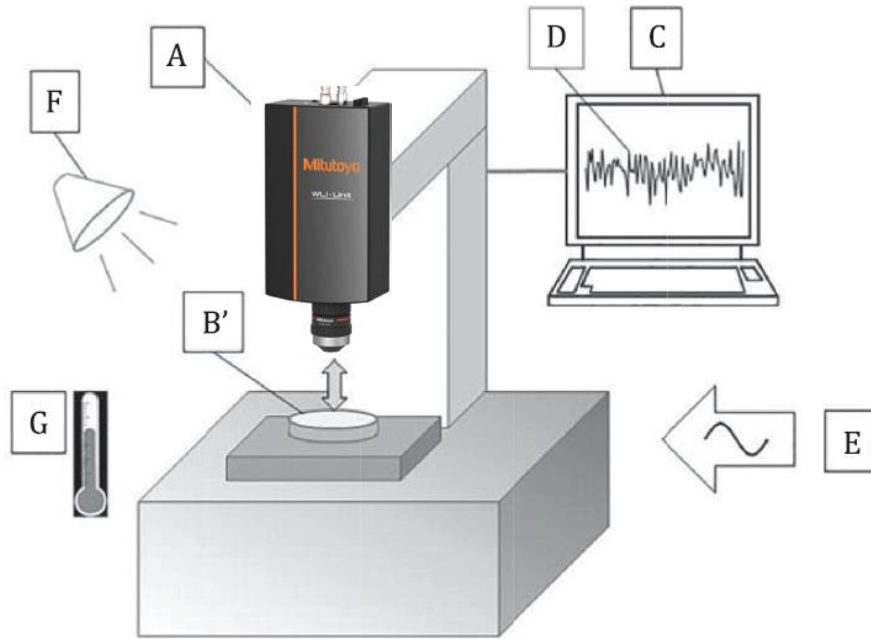


ISO 25178-600
Metrological
Characteristics
(all technologies)

$$S_q = \sqrt{\frac{1}{A} \iint_A z^2(x,y) dx dy} = (141 \pm ??) \mu\text{m}$$

ISO 25178-604
Coherence scanning Interferometry
(White-light interferometry)

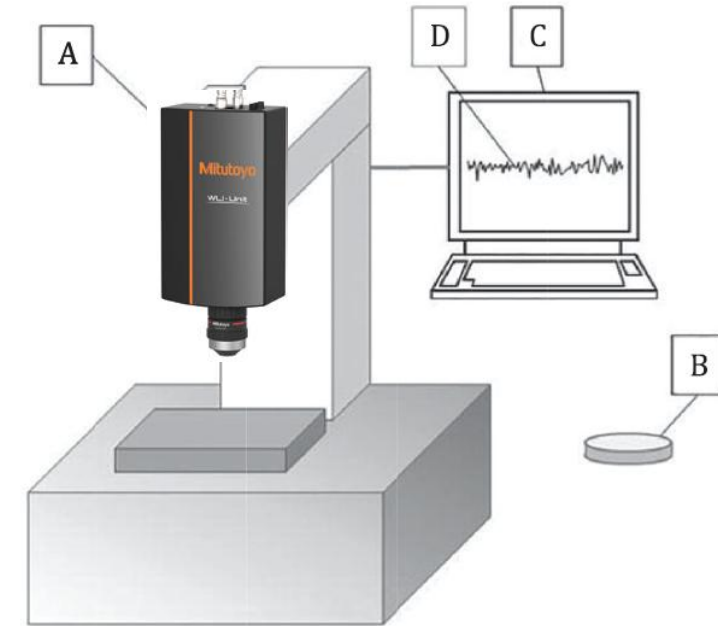
Measurement noise and instrument noise



b) Conditions under which the measurement noise might be assessed for some types of instruments

Measurement noise:

- Actual specimen (may be rough, have form deviations)
- Actual environment (with floor vibration, air turbulence etc.)



a) Conditions under which the instrument noise might be assessed for some types of instruments

Instrument noise:

- Ideal specimen (flat, aligned, reflecting)
- Ideal environment (vibration free)

Colloqually: 'z-size of smallest feature that can be observed'

Measurement noise and instrument noise

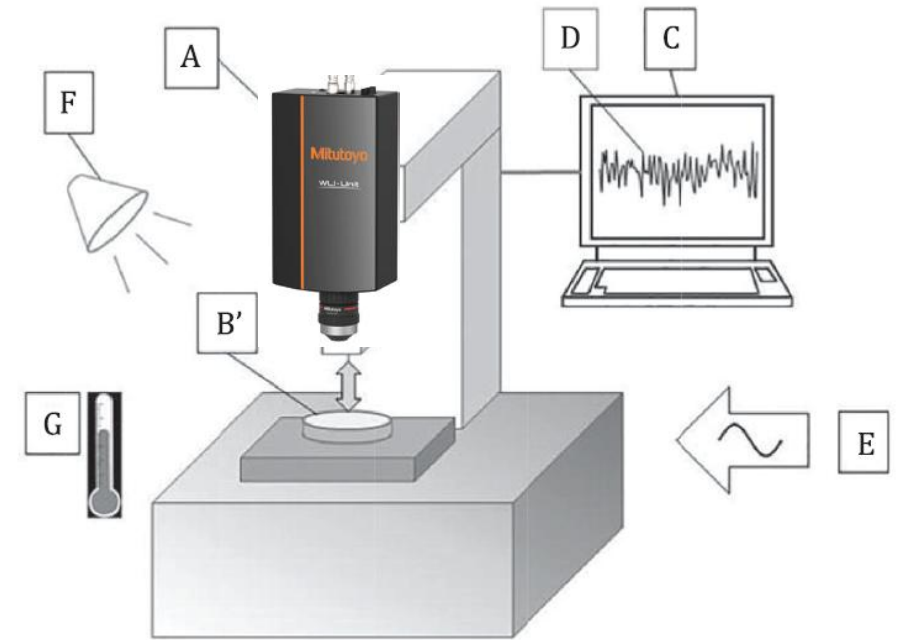
ISO Noise definition ISO 25178-700:

‘effective standard deviation for each measured point $z(x,y)$ when repeating a measurement’

For 2 consecutive measurements:

$$N_M = \frac{1}{\sqrt{2}} S_q(z_1(x,y) - z_2(x,y))$$

Colloqually: ‘z-size of smallest feature that can be observed’



b) Conditions under which the measurement noise might be assessed for some types of instruments

Measurement noise:

- Actual specimen (may be rough, have form deviations)
- Actual environment (with floor vibration, air turbulence etc.)

Measurement noise and instrument noise

ISO Noise definition:

$$N_M = \frac{1}{\sqrt{2}} S_q(z_1(x, y) - z_2(x, y))$$



RMS repeatability:

$$R_{RMS} = \frac{1}{\sqrt{2}} (Sq(z_1(x, y)) - Sq(z_2(x, y)))$$

Confusing specifications:

Resolution, single meas. (rms) 1 nm

- **Sub-nanometer vertical resolution (down to 0.1 nm) at all magnifications**

- Measures how constant the noise is
- Gives low values: commercially interesting

RMS repeatability of surface accuracy: 0.01 nm

- **0.1 ångström resolution over the entire measurement range**
- **<0.2 ångström RMS repeatability,**

Measurement noise and instrument noise

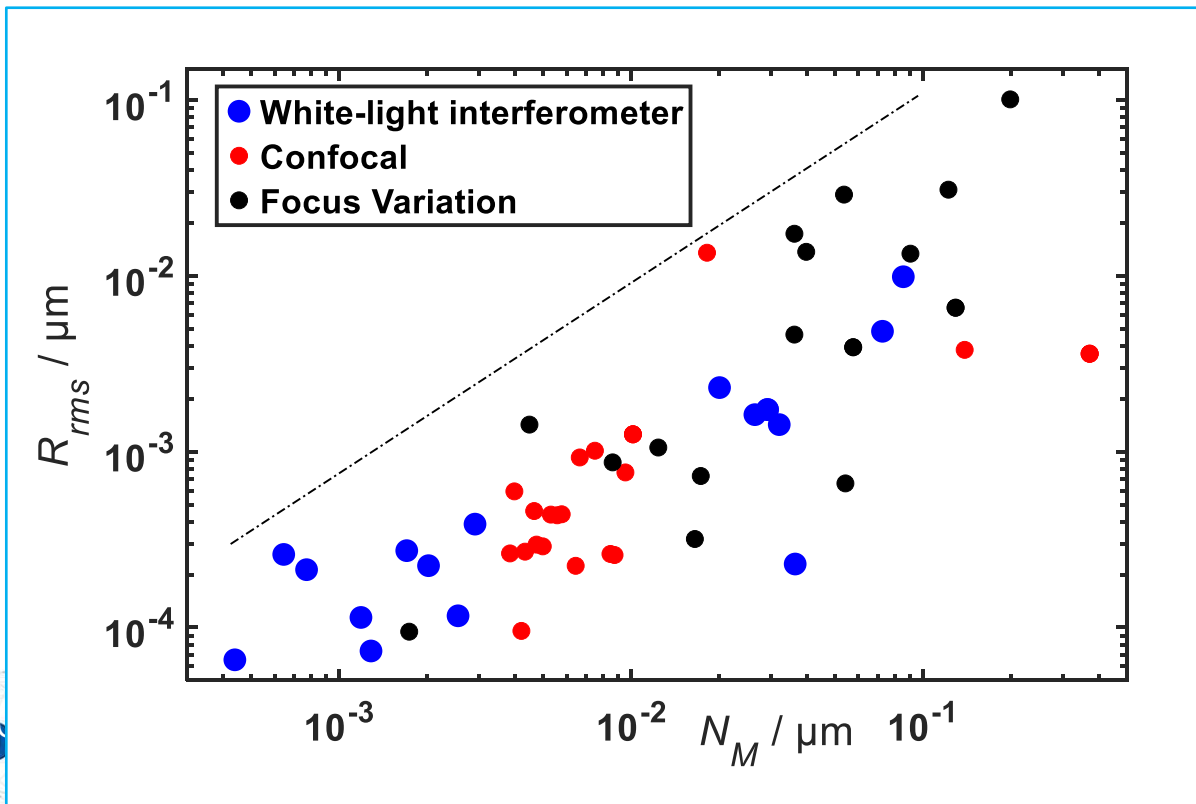
ISO Noise definition:

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RMS repeatability:

$$R_{RMS} = \frac{1}{\sqrt{2}} (Sq(z_1(x, y)) - Sq(z_2(x, y)))$$



CIRP comparison 2018-2020: 48 measurements

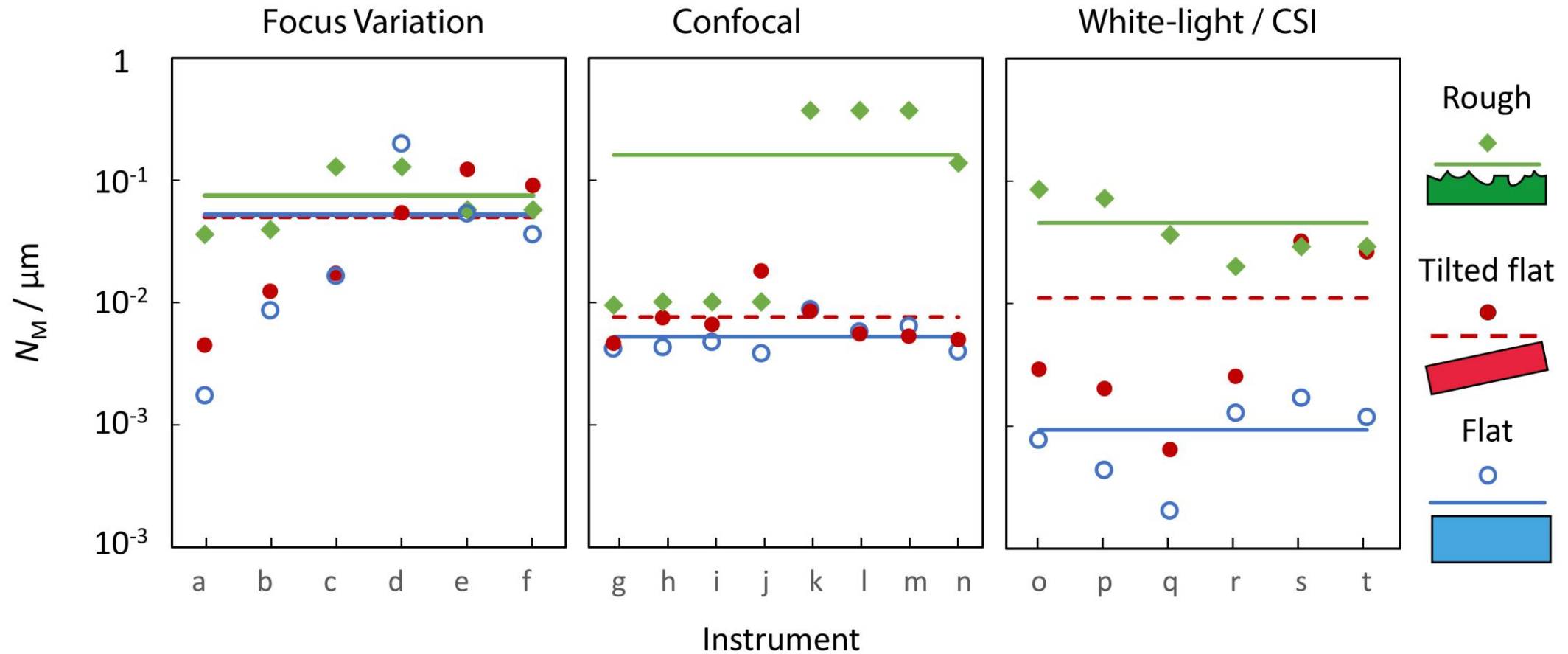
R_{rms} up to 100 times smaller than N_M

Limitations of N_M

- Depends on measurement speed/time
- Depends on lateral resolution/filtering

Measurement noise and instrument noise

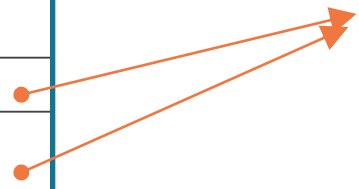
Result CIRP comparison 2018-2020 : large variation between and within technologies



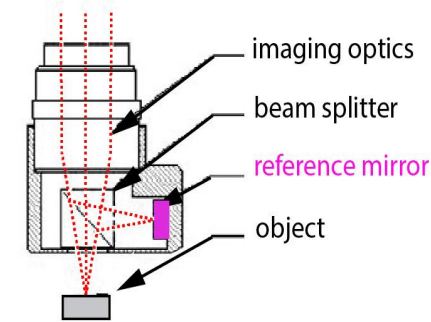
Flatness deviation: 'how will the instrument measure a perfectly flat surface'

Influence quantity
Equivalent wavelength
Mean value of the CSI scan increment
Focus effects
Reference mirror flatness
Optical ray tracing error
Random environmental vibration
Camera noise
Optical lateral resolution
Sampling interval
Optical distortion
Surface films
Dissimilar materials
Surface slopes and discrete step features
CSI scan linearity
Fringe-order errors

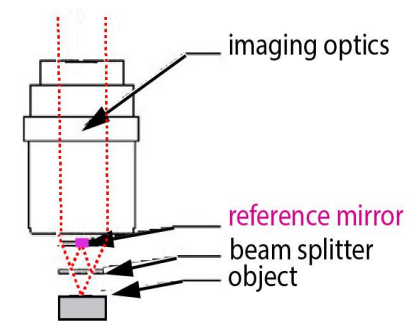
Metrological characteristic
Amplification coefficient
Linearity deviation
Flatness deviation
Measurement noise
Topographic spatial resolution
x-y mapping deviations (Note 1)
Topography fidelity



ISO 25178-600
Metrological Characteristics
(all technologies)



Michelson type



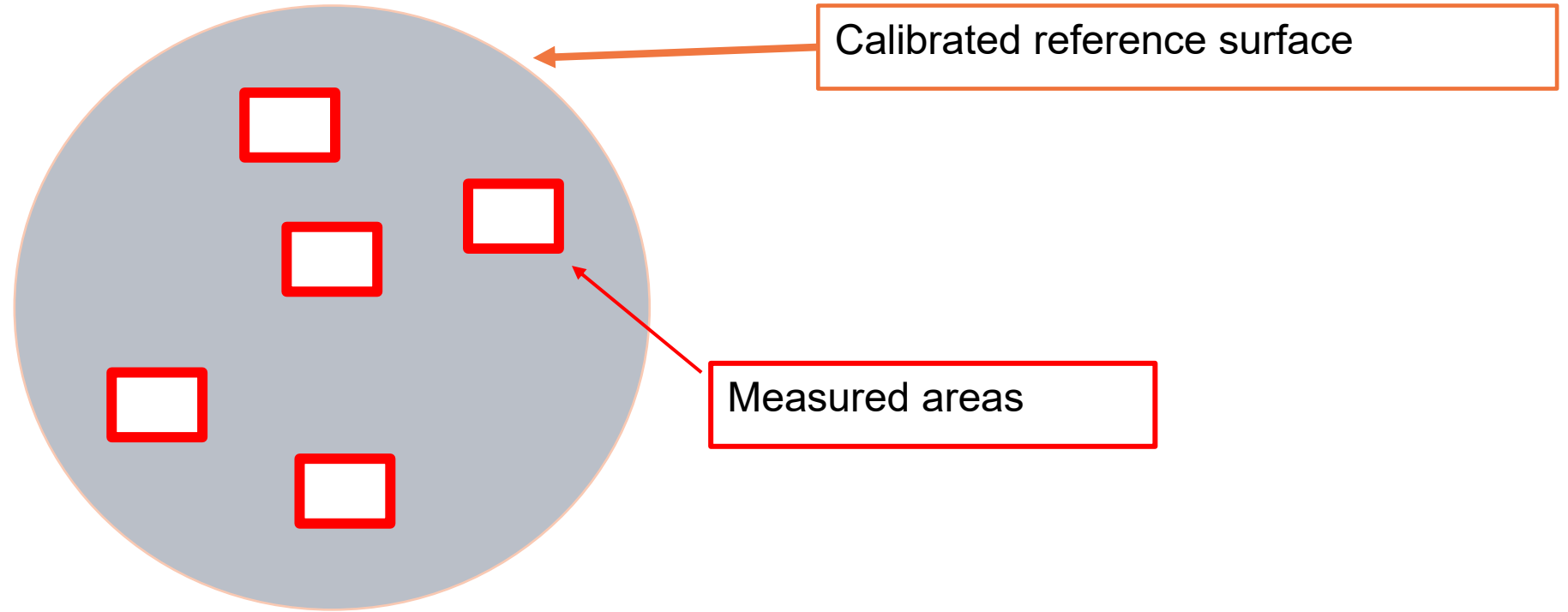
Mirau type

ISO 25178-604
Coherence scanning Interferometry
(White-light interferometry)

Flatness deviation

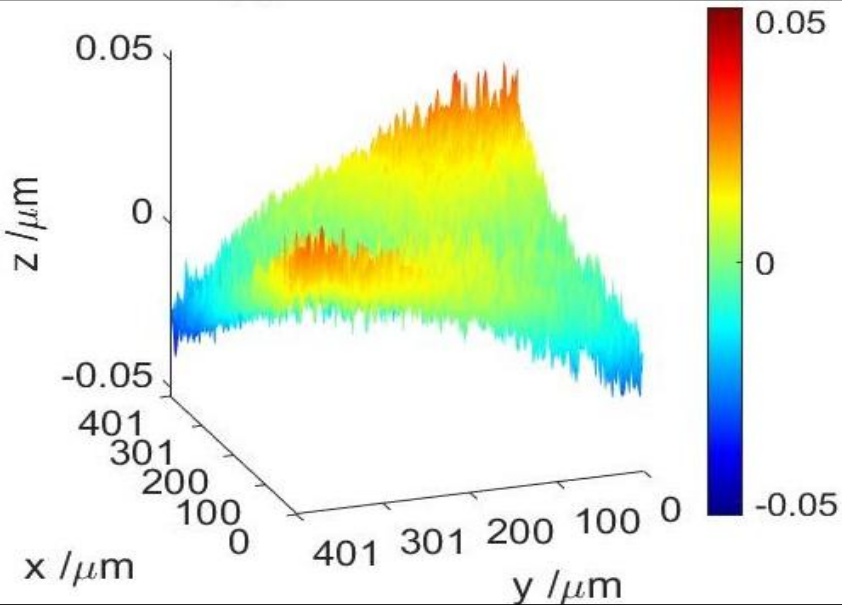
Evaluation method recommended in ISO-25178-700

- Measure nominal flat surface
- Reduce reference surface influence by averaging randomly chosen areas

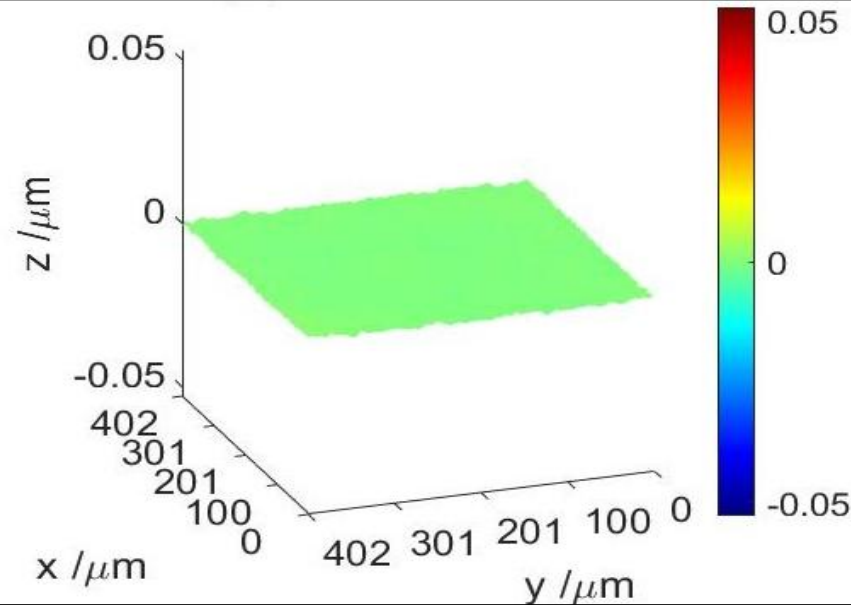


Flatness deviation : result CIRP comparison

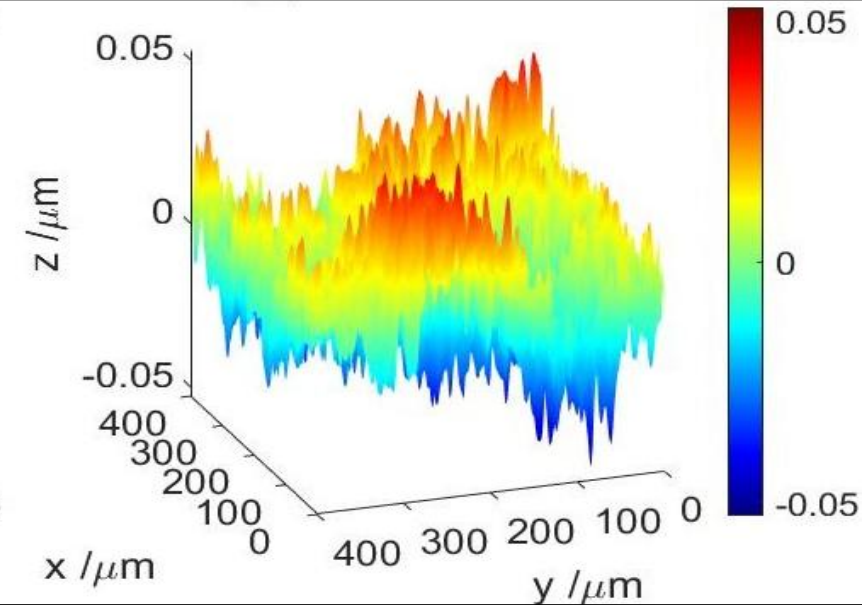
Confocal



White-light



Focus variation



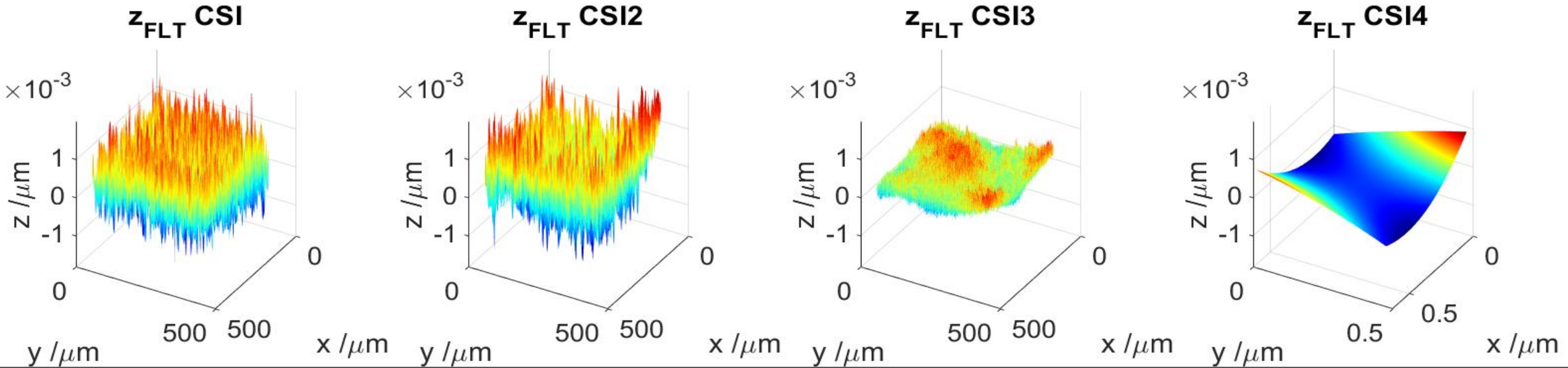
Flatness deviation

Ann.CIRP 71(2022)453-456

Results:

1. Expected: residual curvature of lens focal plane (Confocal, Focus variation);
reference mirror topography (White-light interferometer)
2. Expected trend: $z_{FLT}(FV) \approx z_{FLT}(CF) > z_{FLT}(CSI)$

Flatness deviation : result CIRP comparison



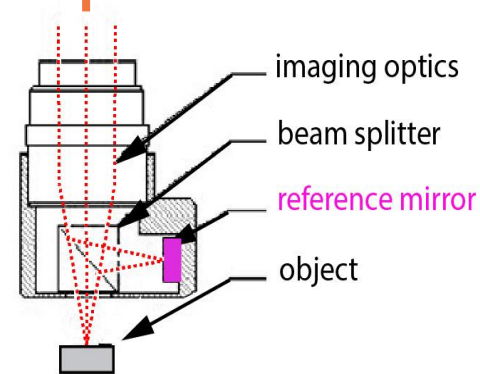
Ann.CIRP 71(2022)453-456

Different CSI / WLI systems: similar performance 1 – 4 nm range

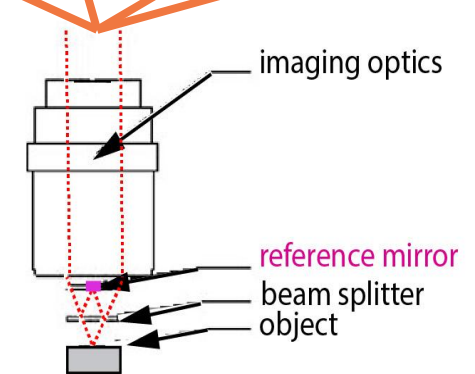
WLI-objectives: the heart of the system

Own development: consider key technology: the WLI objective

Metrological characteristic
Amplification coefficient
Linearity deviation
Flatness deviation
Measurement noise
Topographic spatial resolution
x-y mapping deviations (Note 1)
Topography fidelity



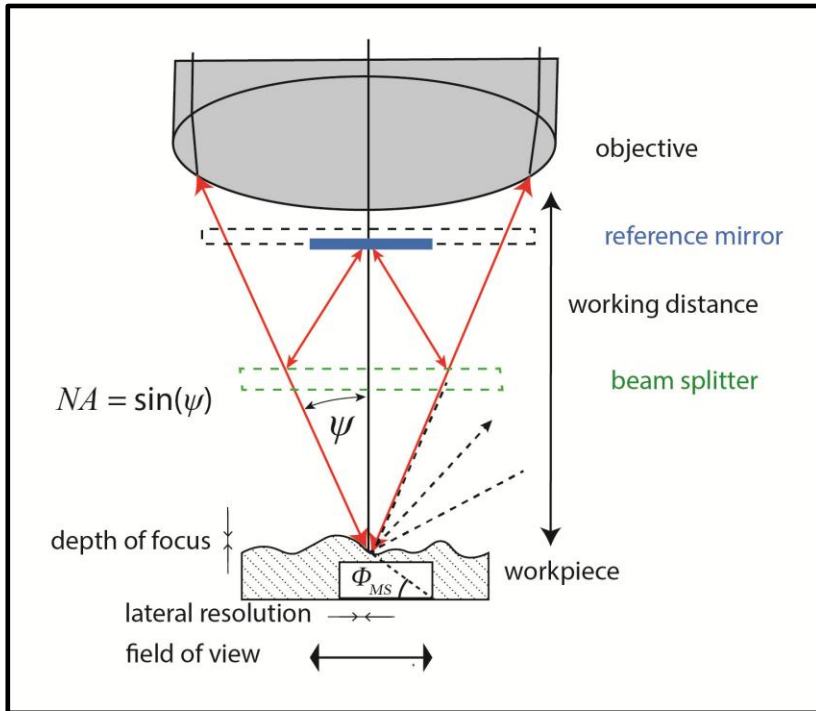
Michelson type



Mirau type

WLI-objectives: the heart of the system

	2.5x	5x	10x	25x	50x
NA	0.14	0.28	0.38	0.50	0.70
Fov/mm ²	3 x 2	1.5 x 1	0.7 x 0.5	0.3 x 0.2	0.15 x 0.1



Design considerations:

- Lateral Resolution : $D_{lim} = 1.2 \cdot \lambda / NA$
- Depth of focus $d_f = \lambda / NA^2$
- Maximum workpiece angle (for specular reflecting surface): $\Phi_{MS} = \sin^{-1} NA$
- Reflectance of reference mirror : should match workpiece: compromise
- No chromatic effects, flat focus field: **plan apochromat** and **flat mirror**
- Rough surface: large field of view, large angles (large NA) : contradictory requirements
- Reference mirror must be in focus: can be adjusted (but not easily)

White-light module

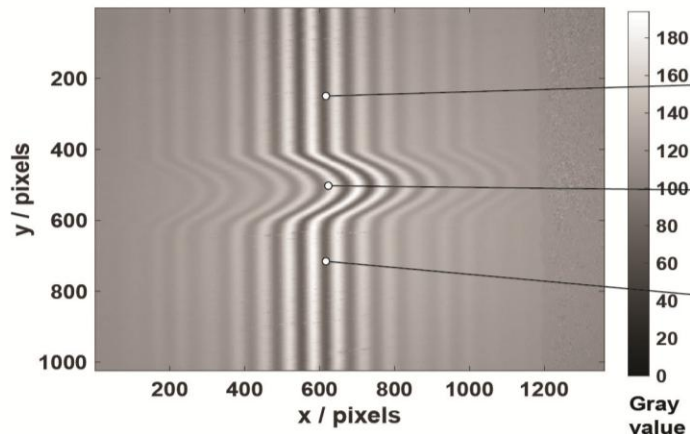
Some design considerations in white-light interferometry:

Signal evaluation : Envelope intensity versus phase:

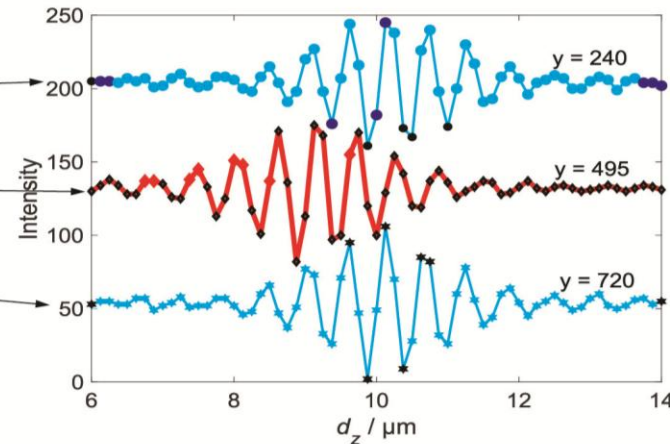
Evaluations:

- 'Envelope' : rather robust, nm-resolution
- 'Phase' : more accurate: sub-nm resolution; more risk of jumps/outliers

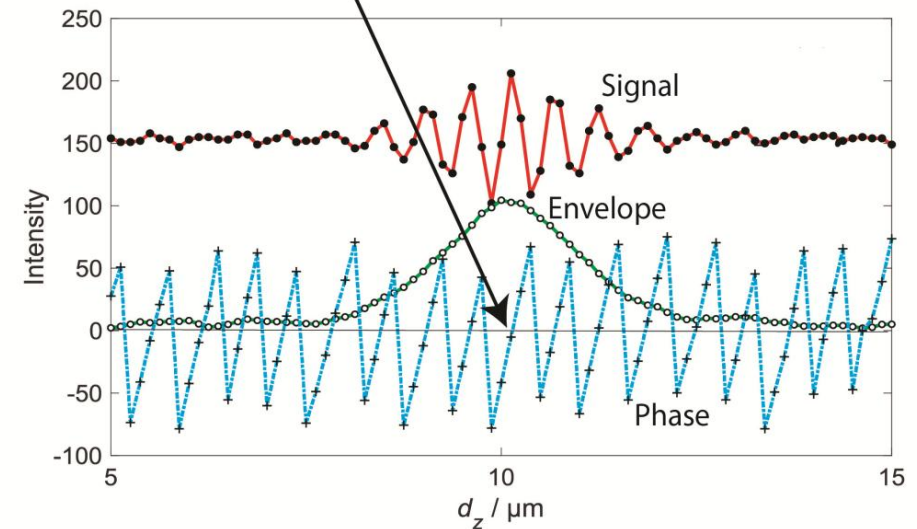
Image of tilted groove



signals of single pixel / height



z-height position



Final height (z-) accuracy affected by

- Signal noise/contrast(range)
- z-position accuracy (vibrations, scale linearity)
- Evaluation method (some magic in robustness, no magic in sub-nm / pm resolution)

White-light module

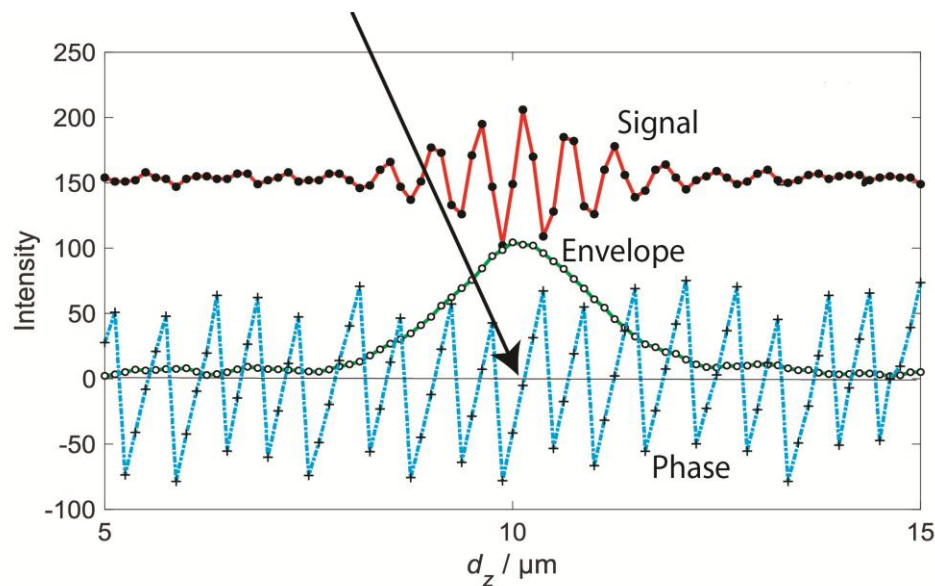
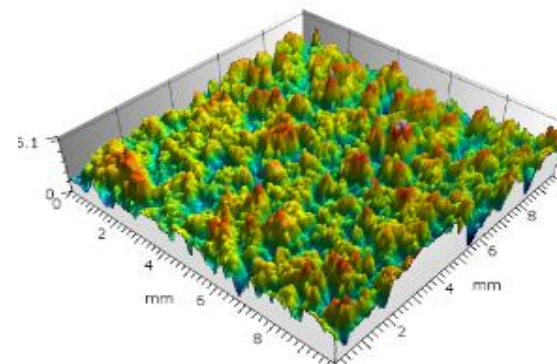
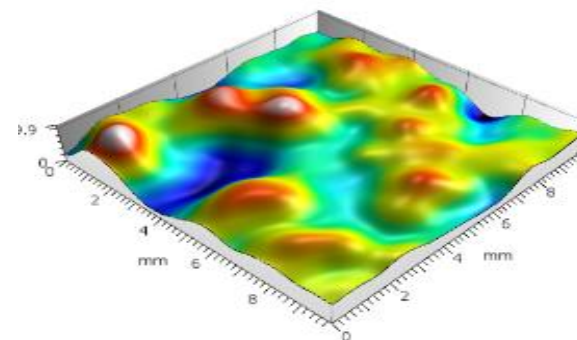
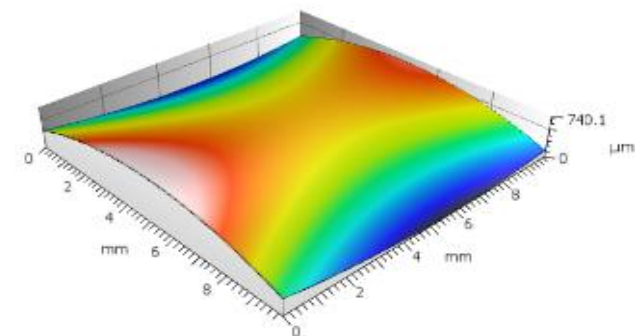
Result of considerations:

Versatile WLI module + line of objectives

- Large vertical range : 4 mm by micro-spindle movement
- White LED-illumination
- z – measurement by internal linear scale
- 816 x 624 pixel camera; 670 frames / s
- 54 $\mu\text{m/s}$ vertical speed
- Envelope and/or phase evaluation
- Output of $z(x,y)$ surface topography
- '4 nm resolution' ; conservative specification, comparable to any other system.



Thank you for your attention



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Deadline

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