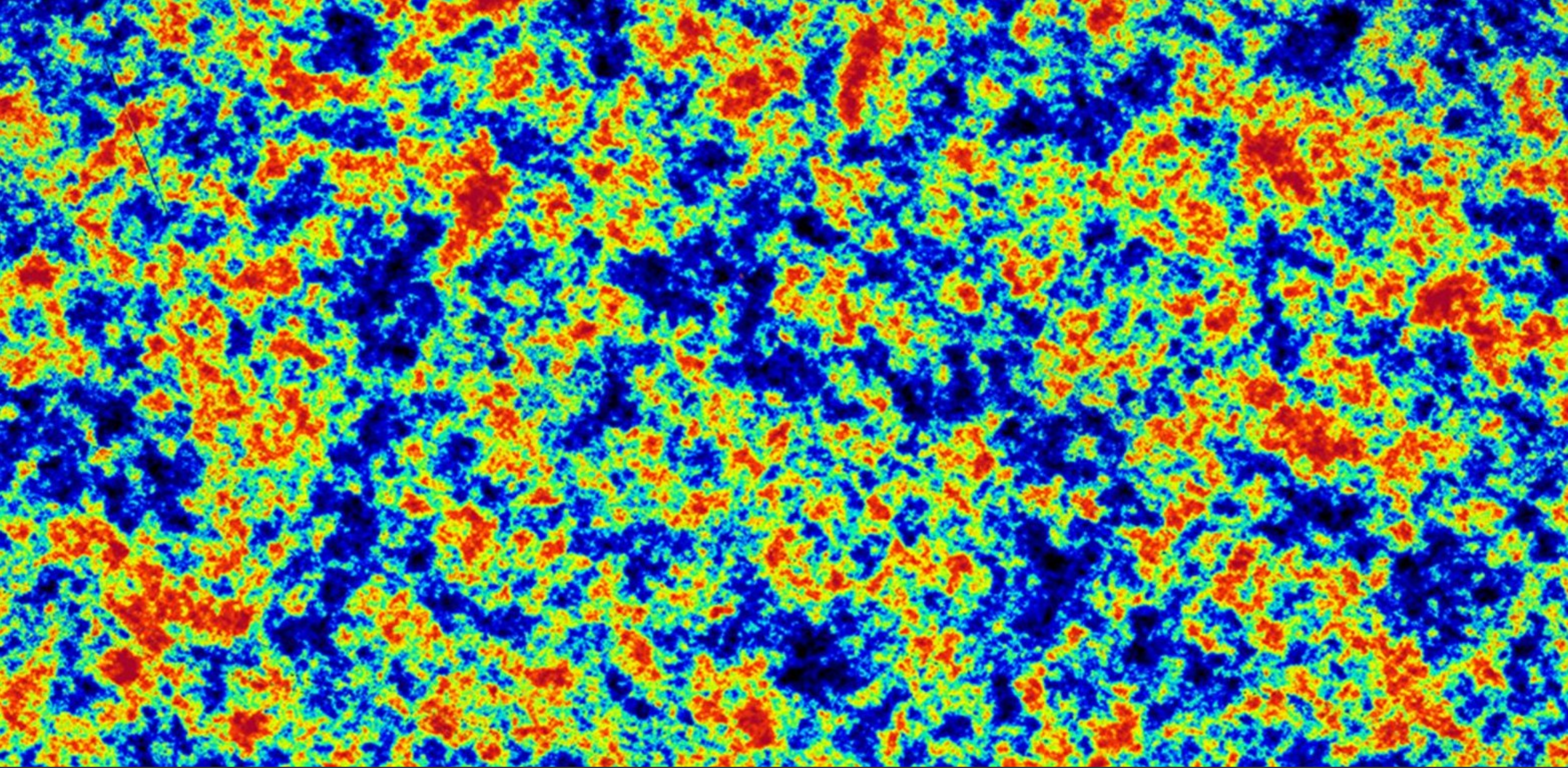
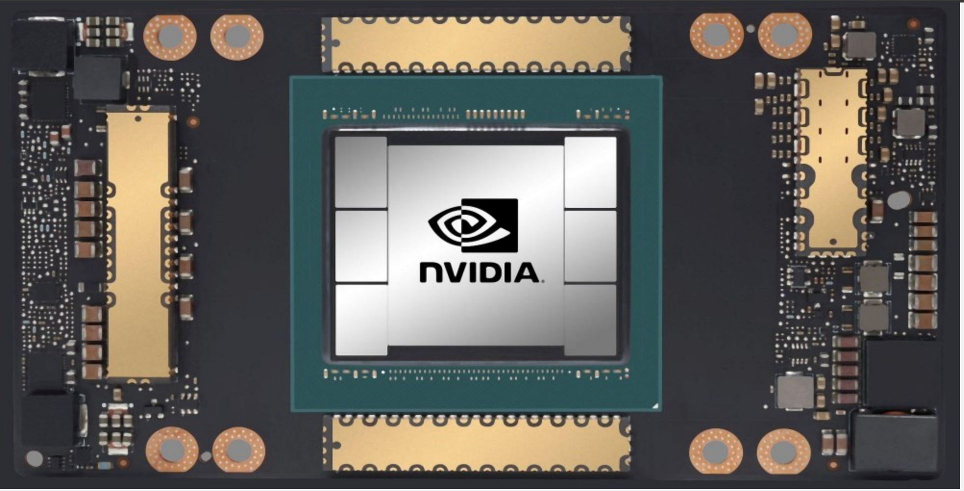


THE TECHNOLOGY OF OPTICAL HIGH PERFORMANCE PROFILERS

smartWLI

advantages of high performance measuring technologies



parallel data processing using advances algorithms

GPGPUs (General Purpose Graphic Processing Units) using thousands of processing cores which are optimized for massively parallel and ultra fast image processing. Even the best CPUs on the market can’t perform at that level. The processing speed is very useful for coherence scanning interferometry because thousands of large image stacks can be evaluated in real time with the following purpose:

- higher resolution in xyz
- scanning of larger areas
- shorter measuring time
- independent from environmental conditions

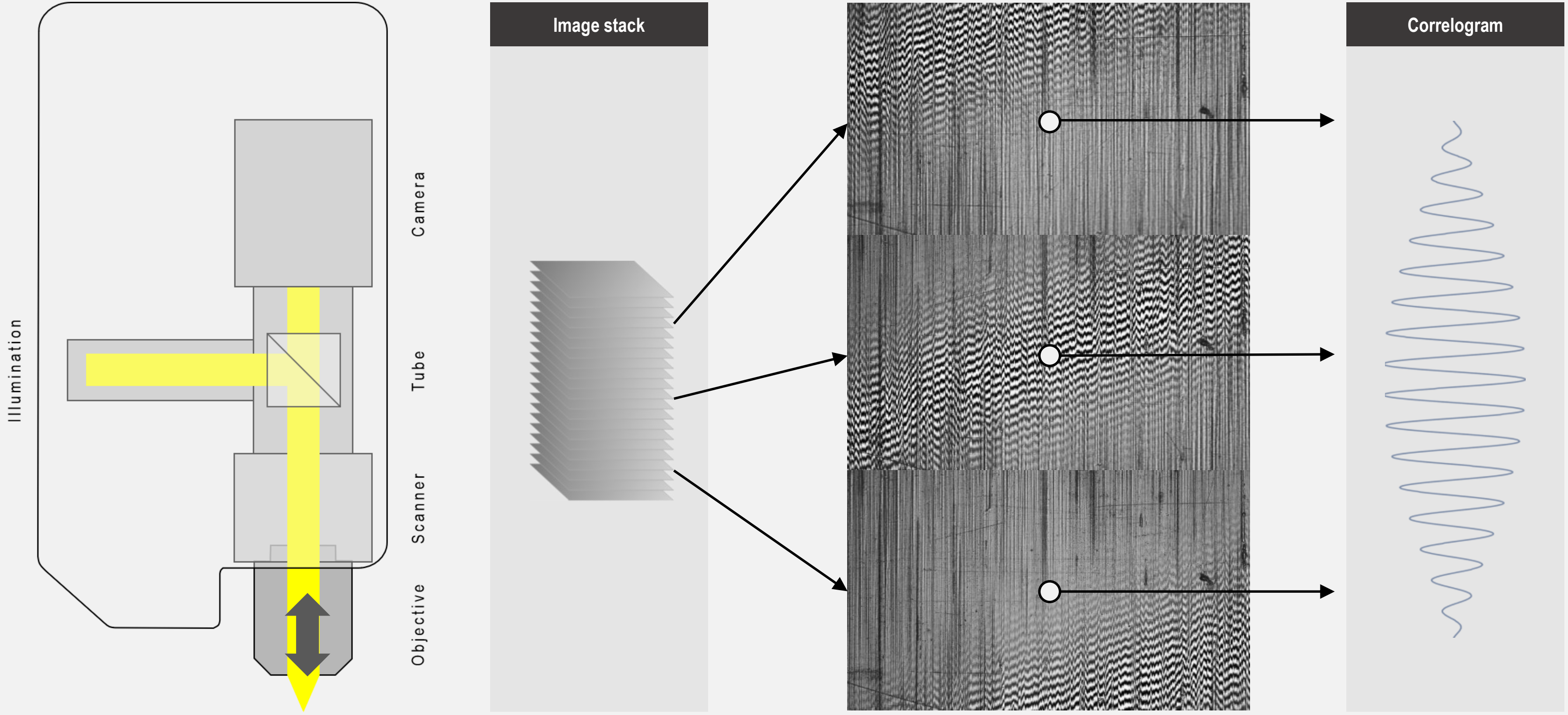
performance comparison

	Core I9 13900K	GTX 1060	RTX 2060	RTX 3060	RTX 4090
release date	2022	2018	2019	2020	expected 2022
FP32 (float) performance	0.74 TFLOPS	4.4 TFLOPS	6.4 TFLOPS	16.2 TFLOPS	82.6 TFLOPS
process size	10 nm	16 nm	12 nm	8 nm	5 nm

GPGPUs are not only much faster than CPUs, they have shown very fast performance improvements in the past years. This unbroke n trend assists the significant and continuous performance improvements of all smartWLI sensors. On the one side this calculation power is useful ly to reduce the noise and analyze signals on very steep object features and on the other side it is the foundation for developing enhanced sensors using faster cameras while still processing the 3D data in real time.

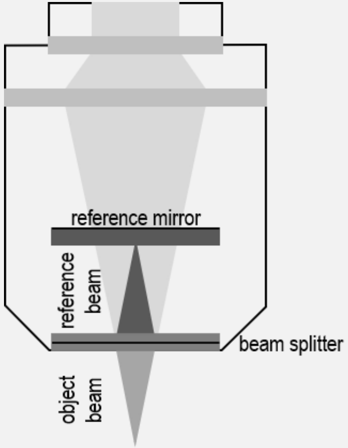
smartWLI

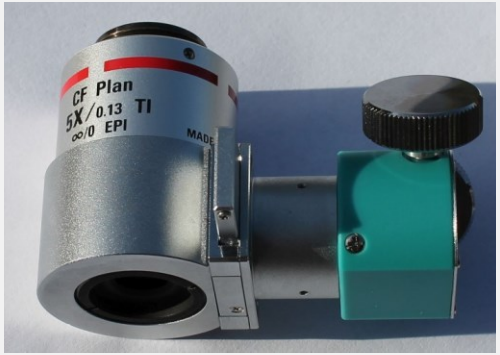
coherence scanning interferometer

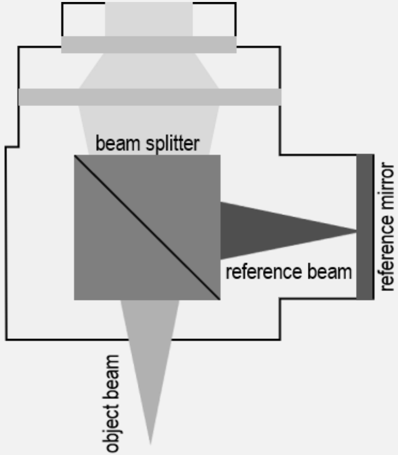


The coherence scanning interferometer realizes the acquisition of an image stack while the scanner is precisely moving the interference objective. For each pixel in the image stack, the interference signal (correlogram) contains the exact height information that is physically when object and reference beam are equidistant in path length.

smartWLI interferometry objectives



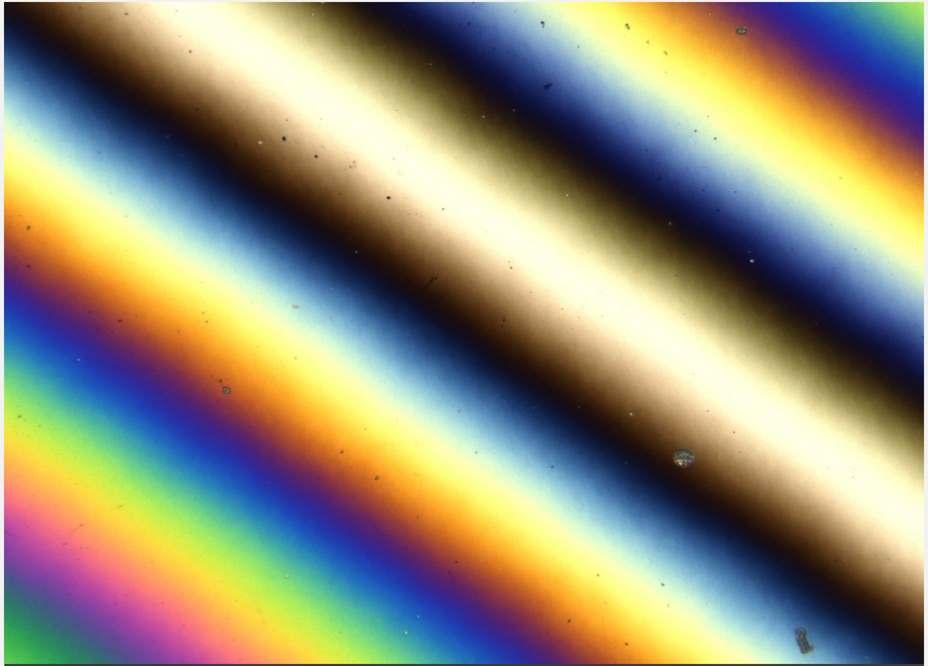




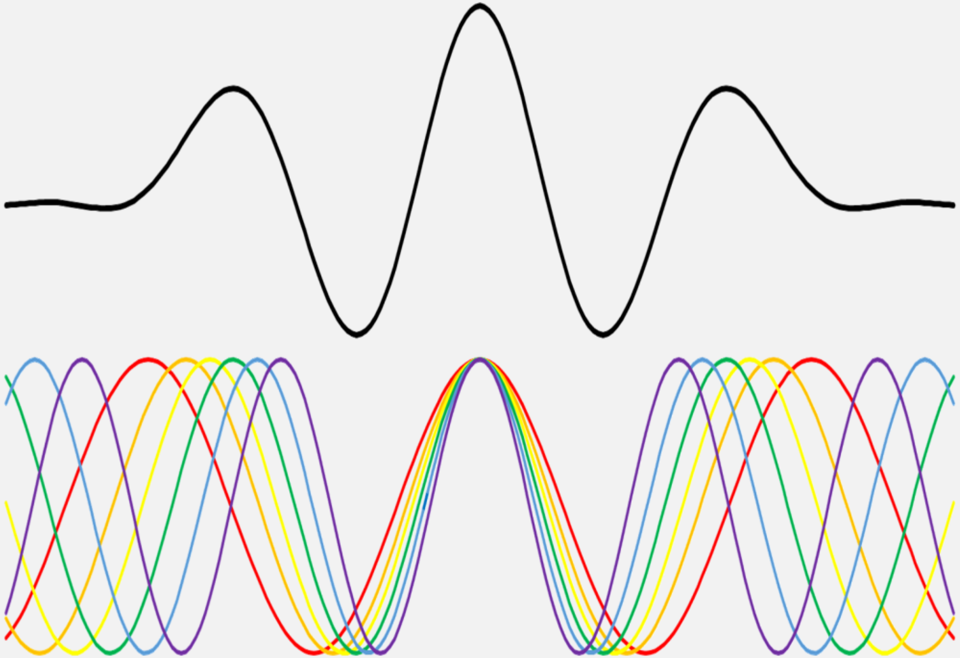
objective type comparison

objective type	Mirau					Michelson	
magnification	115x	100x	50x	20x	10x	5x	2.5x
numerical aperture	0.8	0.7	0.55	0.4	0.3	0.13	0.075
parfocal distance [mm]	45	45	45	45	45	49	90
working distance [mm}	0.7	2.0	3.4	4.7	7.4	9.4	10.3

Coherence scanning interferometers use exchangeable interference objectives that are available with various magnifications. For technical reasons, Mirau objectives are used for higher magnifications like 115x, 100x, 50x, 20x and 10x and Michelson objectives are used for lower magnifications like 5x and 2.5x.



camera image of a mirror / centre of the interference zone

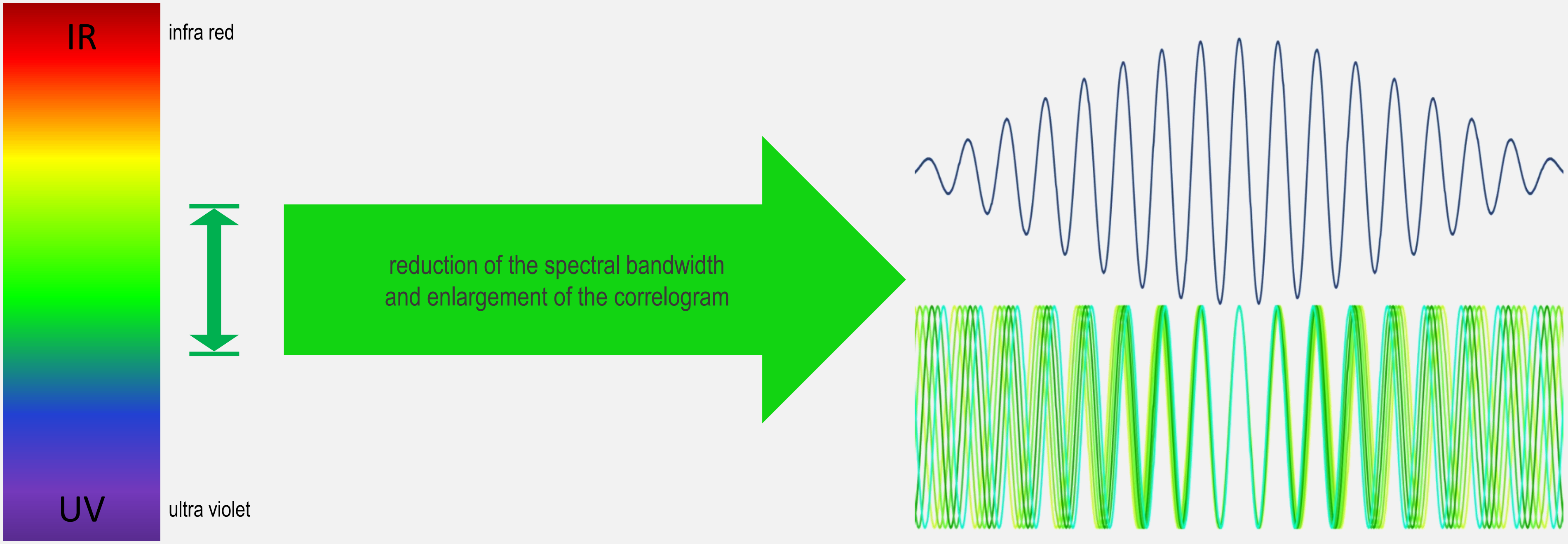


resulting light intensity out of spectral shifted interferences

White light consist of a continuous distribution of various spectral colours. All spectral colours show interferences between reference and object beam. In the centre position where reference beam and object beam have a equal length, all spectral colours have a maximum. Because of the various wave length the second, third … maxima have a shifted position and the resulting intensity of interference is smaller because of a very limited – so called – coherence length of white light.

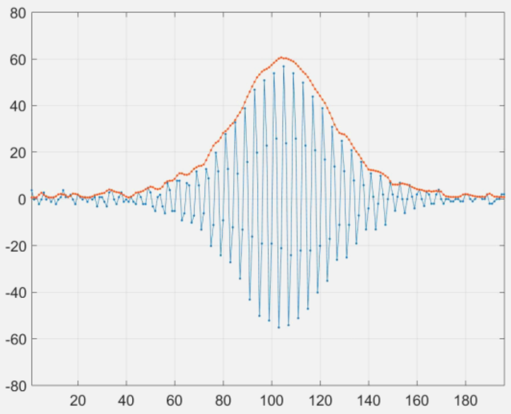
smartWLI

spectral optimization for noise reduction

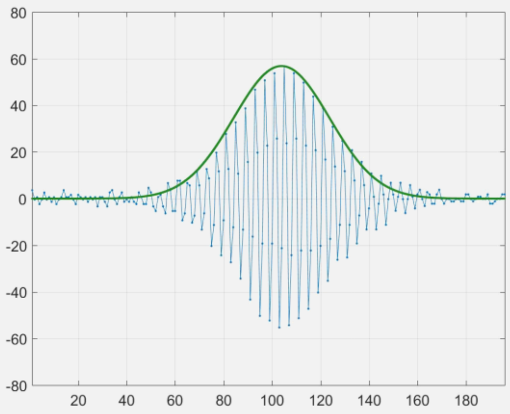


Bigger correlograms with several sinus like intensity variation enable the use of phase-shift algorithms. Such algorithms use the sinus like light intensity variations to increase the height resolution/reduce the noise. In contrary to illumination sources with a smaller coherence length, statistical positioning deviations and the camera noise are filtered more effective. Such algorithms require significant more calculation power. GBS uses its massive parallel image processing expertise for effective and extreme fast data evaluation in real time and without delays.

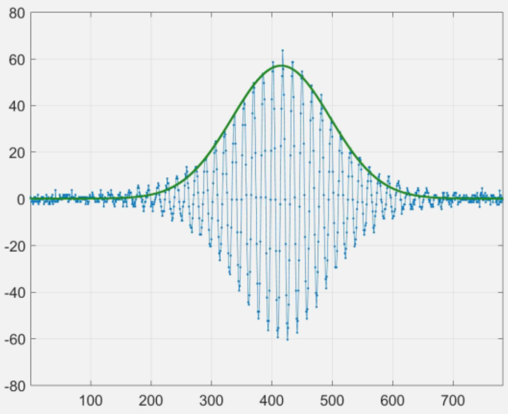
HD-EPSI (high density-extended phase shift interferometry)



VSI (vertical scanning interferometry)
intensity based evaluation of the interference signal



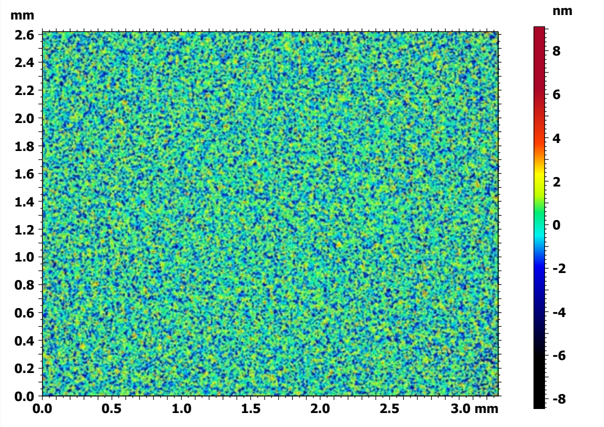
EPSI (extended phase shift interferometry)
phase based evaluation of the interference signal



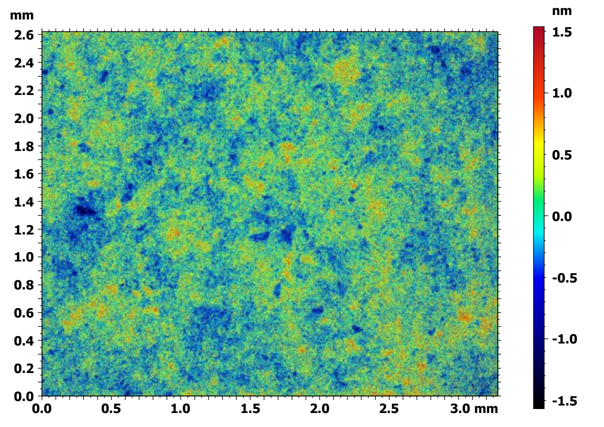
HD - EPSI (high density extended phase shift interferometry) phase based evaluation of the interference signal with a higher density

Shown are the signals and correlogram evaluations of one and the same pixel. The intensity based evaluation of the VSI method show a not ideal red curvature which cause a significant higher noise than the phase based evaluation shown in the green curvatures. Once the increment get smaller (here from $\lambda/8$ -> $\lambda/32$) the evaluation getting better and the noise can reduced further. The advantages are useful if polished surface with a surface roughness below 1 nm should be measured (-> evaluation examples on the next pages)

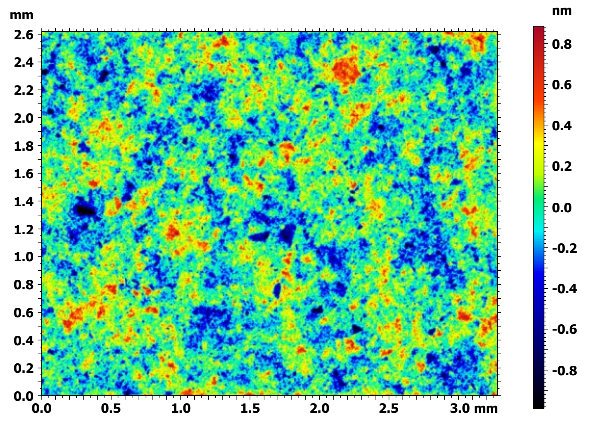
comparison from VSI, EPSI and HD-EPSI



vertical scanning interferometry



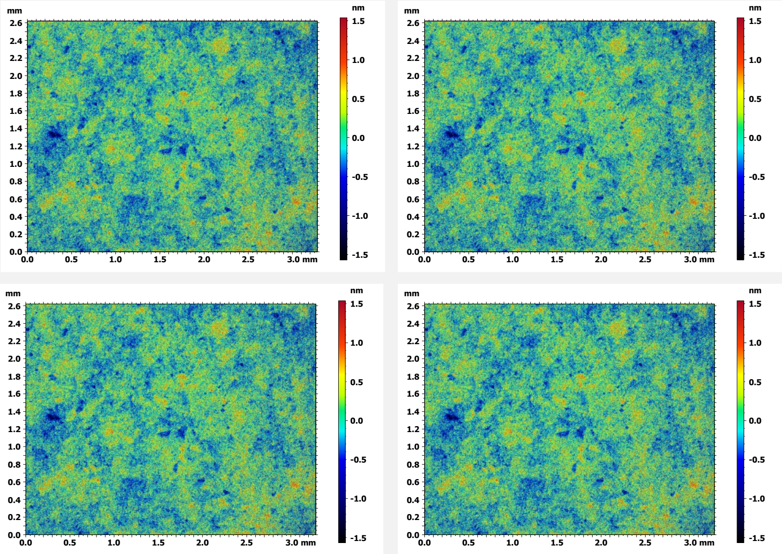
extended phase shift interferometry



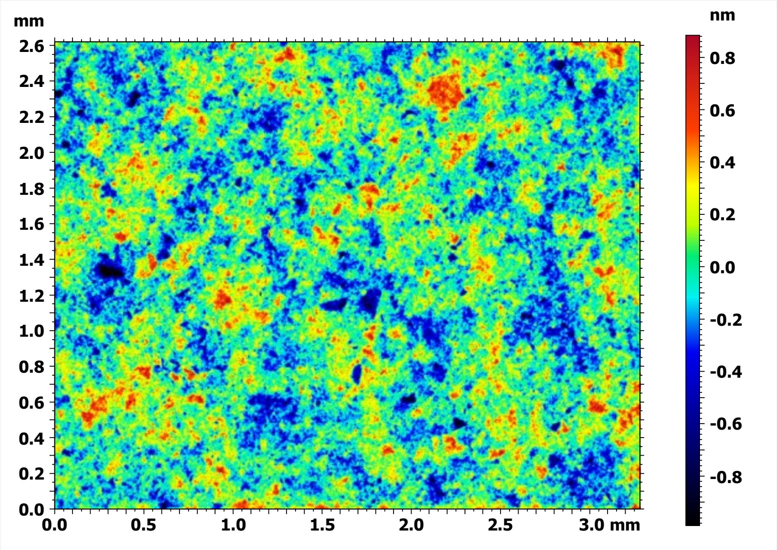
high density extended phase shift interferometry

The images show exactly the same area of a super polished SiC surface with a surface roughness Sq of approximately 0.3 nm. VSI (vertical scanning interferometry) doesn't provide the required height resolution to quantify the topography. EPSI with an much higher resolution and a topography reproducibility (average noise) of approximately 0.1 nm make some structures visible but still looks noise compared with a HD-EPSI scan of the same area.

smartWLI profile averaging



4 scans using extended phase shift interferometry



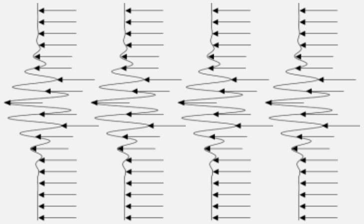
average 3d image out of 4x EPSI scans

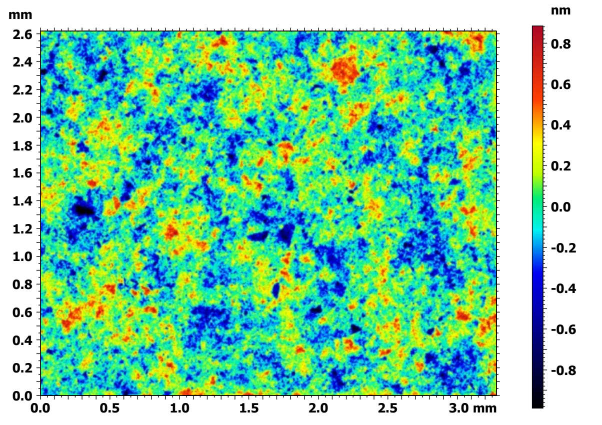
- profile averaging is a common method for noise reduction
- random noise has an Gaussian–like distribution

$$\text{resulting noise} = \frac{\text{original noise}}{\sqrt{\text{number of scans}}}$$

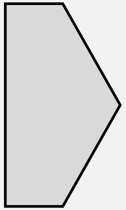
- significant noise reduction through a larger number of scans
- a larger number of scans require a significantly higher measuring time
- drift effects – specifically while using higher magnification objectives – may reduce the lateral resolution
- averaging with a higher number of scans is partially used to improve the system specification and therefore meaningless without the specification of the required measuring time

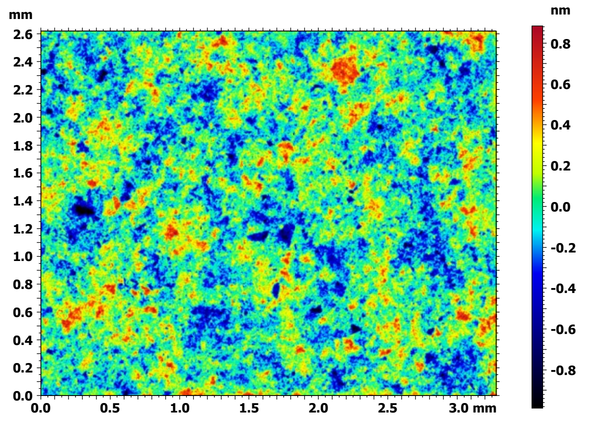
comparison between HD-EPSI and the profile averaging



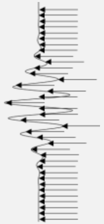


average 3d image out of 4x EPSI scans





high density extended phase shift interferometry



comparison between HD-EPSI and EPSI with profile averaging

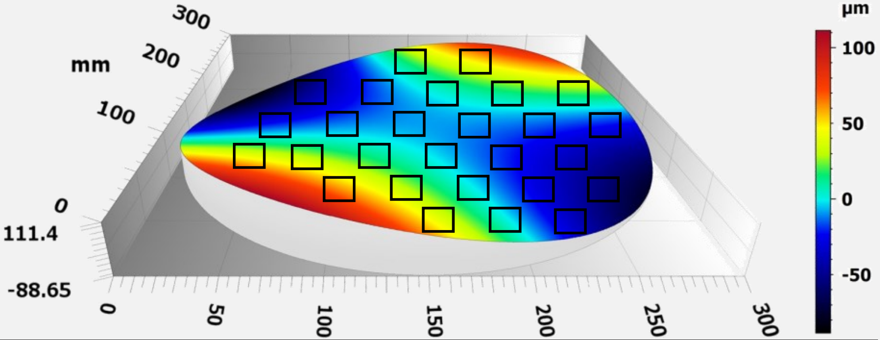
- 4x EPSI scans acquire as many images out of the interference zone as a single scan using a high density scan with 4x smaller increment between images
- both methods reduce the noise level and the result is similar under ideal environmental conditions
- on the one side the scanning speed of HD-EPSI drops down to ¼ of the scanning speed of EPSI but has the following advantages
    - scans are done against gravitation from the lowest point to the highest one and HD-EPSI doesn’t require the scanner to reposition to the start point
    - it requires only 1 acceleration phase of the objective
    - scanning speed is lower and reduces motion blur, which enables longer integration times for the camera
    - averaging calculation isn’t necessary
- practical tests have shown the following advantages
    - HD-EPSI scans are much faster than multiple EPSI scans with profile averaging
    - HD-EPSI shows a lower sensitivity against vibration and drift effects
- HD-EPSI requires more memory and calculation power of the GPGPU for real time evaluation of 3D data

smartWLI

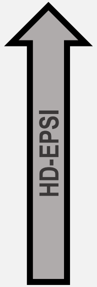
advantage of extreme fast prescans

The challenge to measure multiple position on a super polished wafer:

- polished wafer have extreme smooth surfaces with roughness values below 1 nm – sometimes even between 0.1 and 0.3 nm but usually a much larger wafer bow
- this requires high resolution measurements using HD-EPSI scans or even HD-EPSI scans combined with profile averaging and an therefore moderate scanning speed
- the wafer bow of several 100 µm requires a longer scanning range
- higher scanning ranges with a lower scanning speed for extreme resolution could extend the measuring time
- specifically for larger wafers with multiple measuring position a dual approach with a extreme fast prescan followed from a high resolution scan with a limited scanning range can reduce the measuring time significant
- below a calculation sample for a typically situation
- the time benefit depends from the application but could be more dramatically if sensors with a lower scanning speed get used

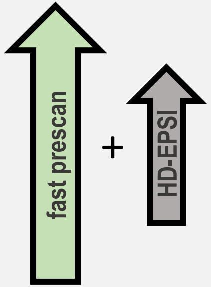


measuring task: local control of the polishing processes
on wafer with a bow of app. 200 µm with multiple single scans



standard scanning time:

- scanning range 200 µm
- scanning speed HD-EPSI with 17 nm increment and full resolution = 16 µm/s
- scanning time = 200 µm / 16 µm/s = 12.5 s
- scan preparation and data processing app. 0.5 s
- **complete measuring time app. 13 s**

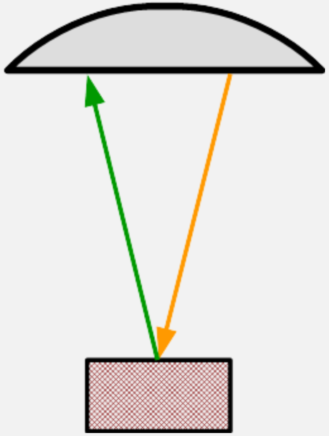


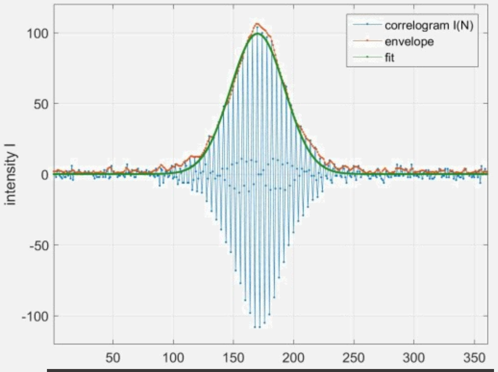
accelerated scanning time using a fast prescan

- scanning range 200 µm
- fast prescan: decimation 5 and increment 200 nm = 1029 µm/s
- fast prescan = 200 µm / 1029 µm = 0.2 s
- scan preparation and data processing app. 0.5 s
- scanning range around the wafer = 10 µm
- scanning time = 10 µm / 16 µm/s = 0.6 s
- scan preparation and data processing app. 0.5 s
- **complete measuring time app. 1.8 s**

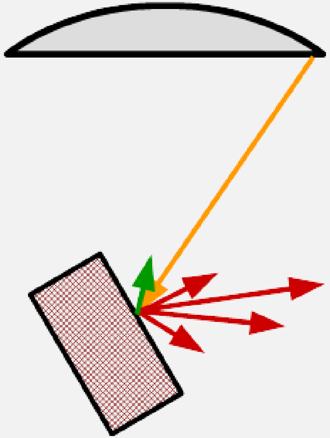
smartWLI

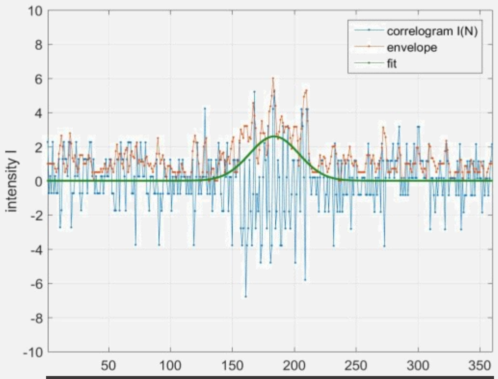
advanced algorithms for steep surface features





interference signal – smooth surface





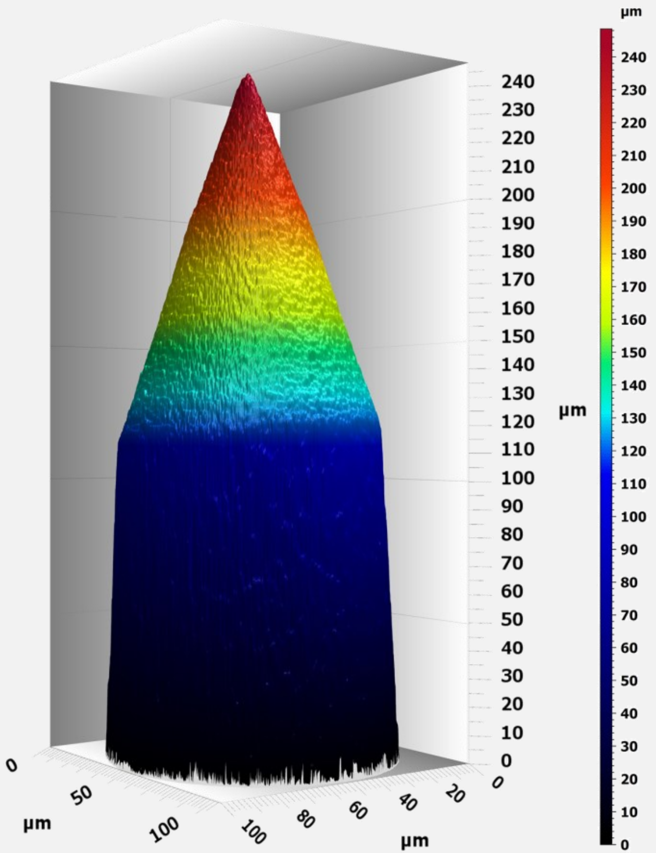
interference signal – inclined surface

maximum angle for high reflective surfaces

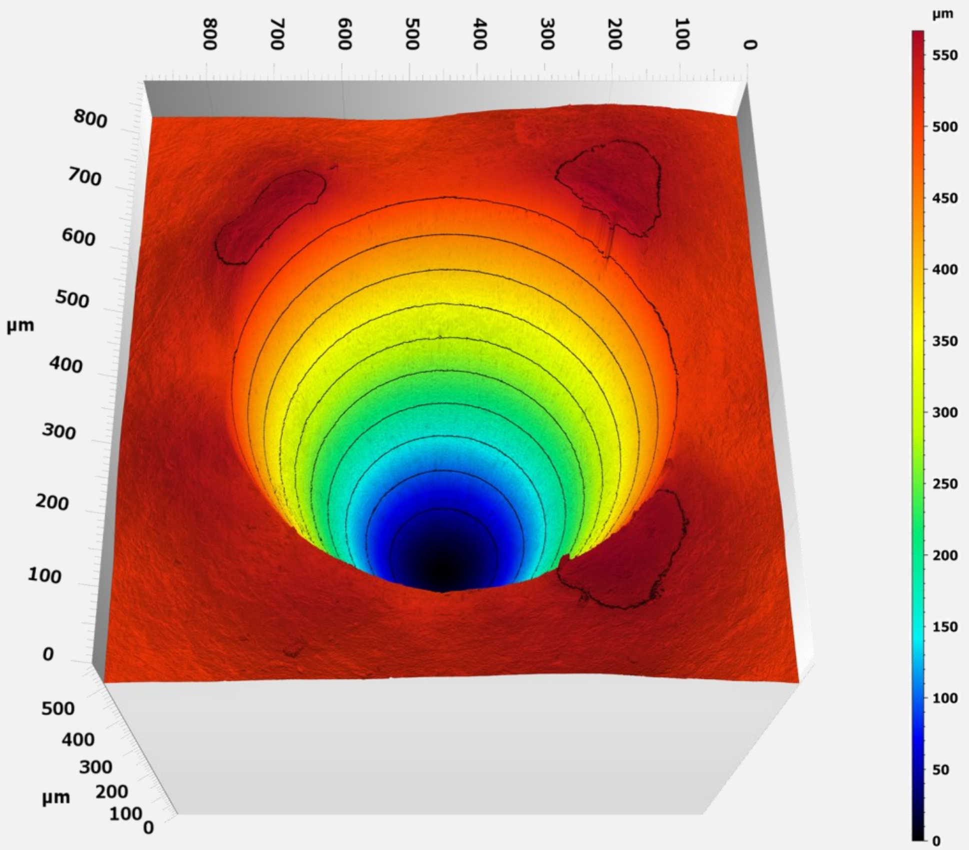
magnification	2.5x	5x	10x	20x	50x	100x	115x
numerical aperture	0.075	0.13	0.3	0.4	0.55	0.7	0.8
max. angle	4.3°	7.4°	17.5°	23.6°	33.4°	44.4°	53.1°

All microscopic optical area scanning devices which project and receive the light through the same objective have a limited maximum angle for high reflective surfaces. Once the angle is too big an objective with a higher aperture is necessary. However, most surfaces scatter at least a small part of the light diffuse and back into the objective. The resulting signals can be analysed but require advanced algorithms since the interference contrast goes down.

samples for steep concave and convex surfaces



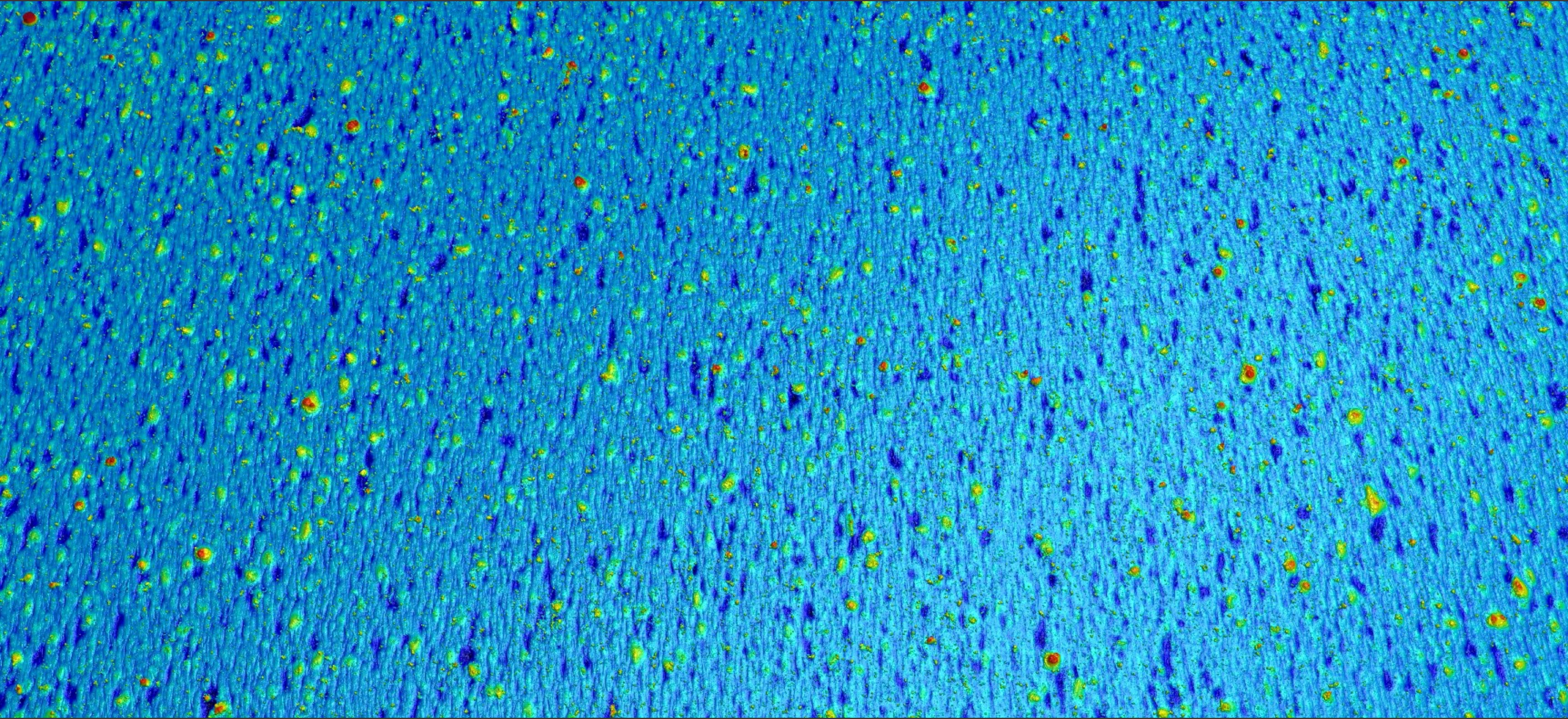
needle to manufacture spinnerets



“lens” to focus x-ray beams

smartWLI

firebolt, 5x objective – 3d printed metal surface

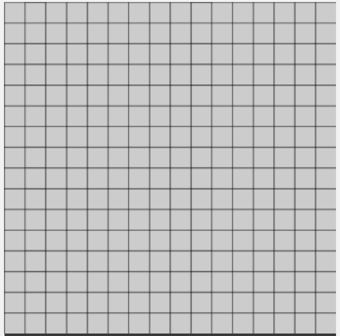


200 µm 30 mm

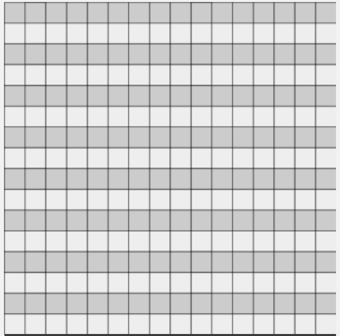
advanced algorithms not only reduce the noise for the scanning of sub nanometer features but also allow fast scans of high sloped structures using low magnification objectives

smartWLI acceleration using decimation

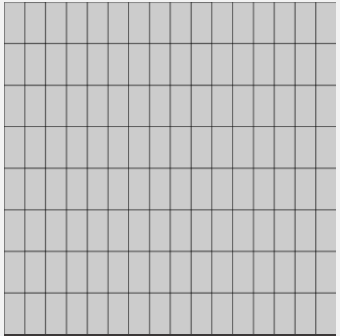
the principle of line decimation applied in firebolt



partial area out of 1280 x 1024 pixel

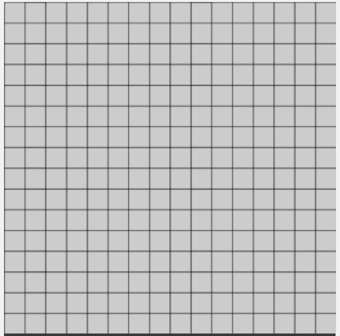


active pixel – decimation 2

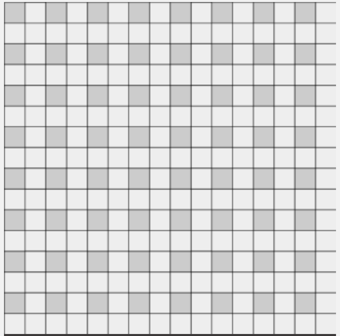


result: 1280 x 512 pixel

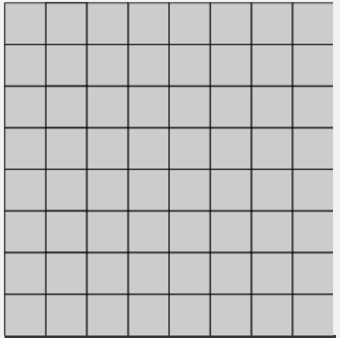
the principle of decimation applied in compact, extended, extended range and next with the 2.3 MP camera



partial area out of 1920 x 1200 pixel



active pixel – decimation 2 x 2



result: 960 x 600 pixel

smartWLI firebolt:

- 1.3 MP; 10 GigE interface; bandwidth of 1000 MByte/s; 935 f/s (full resolution)
- allows line decimation with a factor 2 … 15

smartWLI compact, extended, extended range and next with an 2.3 MP camera:

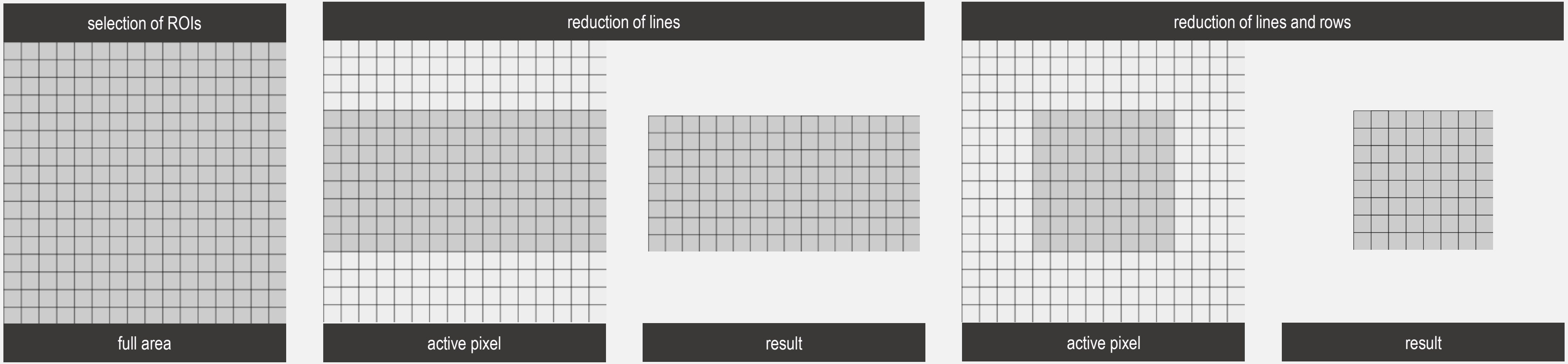
- 2.3 MP; USB 3.0 interface; bandwidth of 400 MByte/s; 169 f/s (full resolution)
- allows area decimation with a factor 2 x 2 in x and y direction

Decimation is a method to reduce the number of used pixel/measuring points and accelerate the scanning speed. The method of decimation doesn't change the scanning area but reduce the pixel/measuring point density inside of the scanning area. Decimation has the significant advantage compared to the often used binning that the interference contrast on rough and inclined surfaces stays unchanged.

	firebolt, 1.3 MP camera - scanning speed - µm/s		
decimation	increment 17 nm	increment 70 nm	increment 200 nm
full area	16	65	206
2	32	131	411
3	48	196	617
4	64	262	823
5	79	327	1029
6	95	393	1234
7	111	458	1440
8	127	524	1646
9	143	589	1851
10	159	655	2057
11	175	720	2263
12	191	785	2468
13	207	851	2674
14	223	916	2880
15	238	982	3086

	various sensors, 2.3 MP camera - scanning speed - µm/s		
decimation	increment 17 nm	increment 70 nm	increment 200 nm
full area	2.8	11.4	34.2
2 x 2	9	36	108

smartWLI acceleration using ROIs (reduced areas of interest)



	1.3 MP camera		2.3 MP camera		5 MP camera	
smartWLI sensors	firebolt		compact, extended, extended range, next		compact, extended, extended range, next, nanoscan	
feature	pixel / measuring points	speed - f/s	pixel / measuring points	speed – f/s	pixel / measuring points	speed - f/s
full area	1280 x 1024	935	1920 x 1200	169	2456 x 2054	77
half lines	1280 x 512	1800	1920 x 600	350	2456 x 1028	148
half lines / half rows	640 x 512	2100	960 x 600	600	1228 x 1028	148
max. speed	1280 x 8	84000	1920 x 36	3200	2456 x 2	1958

ROIs are an alternative method to accelerate the sensor speed. In contrary to the decimation, it keeps the measuring point density but reduces the scanning area (field of view). This acceleration is interesting for inline measurements under vibration if partial areas include all features or several lines are suitable to evaluate 2d line roughness parameters in contrary to 3d roughness parameters.

smartWLI point density and optical lateral resolution

Advantage and limitations of optical resolution and point density to qualify optical 3d profilers:

- The basis of the definition of the optical resolution is the ability of the optical system to separate 2 different light sources. If the optics is able to separate them, it is practically only possible if the point density is significantly higher.
- To select a fitting device with a suitable objective for your application both optical resolution and point density have to be significantly smaller than the features you want to measure.
- Once the point density drops far below the optical resolution, the practical improvements in resolution of the measured surface feature will be limited.
- Please note that there isn't a general accepted way to specify the optical resolution. Individual systems with different measuring principles, different types of data processing, utilizing noise reduction techniques as well as filtering processes can not be compared using either optical resolution or point density.

objective and system comparison

magnification	2.5x	5x	10x	20x	50x	100x	115x	
aperture	0.075	0.13	0.3	0.4	0.55	0.7	0.8	
optical resolution Rayleigh criterion [µm]	4.23	2.44	1.06	0.79	0,58	0.45	0.4	green LED
	3.78	2.18	0.95	0.71	0.52	0.41	0.35	blue LED nanoscan
optical resolution Sparrow criterion [µm]	3.26	1.9	0.81	0.61	0.44	0.35	0.31	green LED
	3.10	1.79	0.78	0.58	0.42	0.33	0.29	blue LED nanoscan
point density 1.3 MP camera [µm]	5.2	2.6	1.3	0.65	0.26	0.13	0.11	
point density 2.3 MP camera [µm]	3.8	1.9	0.96	0.48	0.19	0.1	0.08	
point density 5 MP camera [µm]	2.8	1.4	0.69	0.35	0.14	0.07	0.06	
point density 5 MP camera / nanoscan [µm]	1.4	0.7	0.35	0.175	0.07	0.035	0.03	

Rayleigh criterion:

- light intensity has to drop to 73.5 of the max. intensity between the light sources
- standard approach for microscopic observations with the human eye

$$\mathbf{resolution} = \frac{\mathbf{0.61} * \boldsymbol{\lambda}}{\mathbf{aperture}}$$

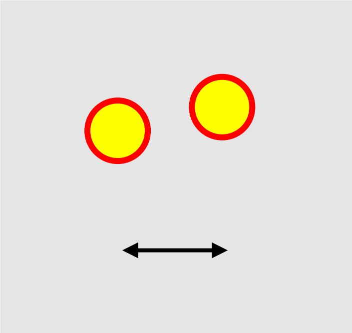
Sparrow criterion:

- limit where the light intensity start to drop below the light intensity of the light sources
- address the higher sensitivity of matrix cameras to visualize smaller intensity differences

$$\mathbf{resolution} = \frac{\mathbf{0.47} * \boldsymbol{\lambda}}{\mathbf{aperture}}$$

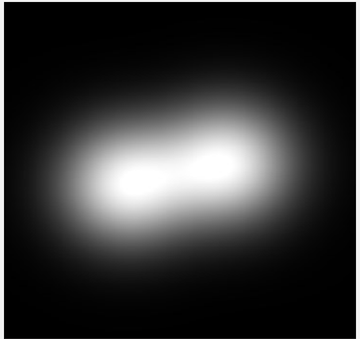
smartWLI

microscope image analysis compared to the 3d scanning



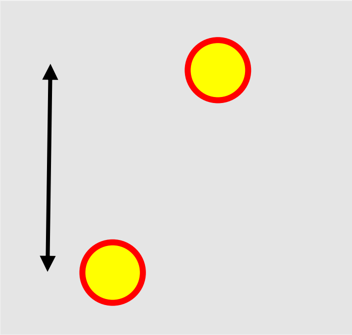
lateral spacing

separation possible

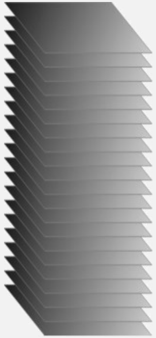


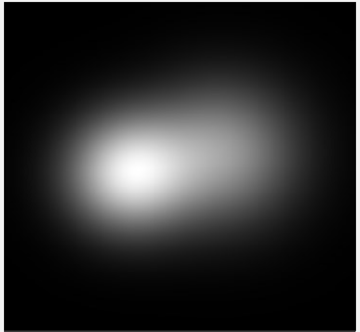
separation limit

separation impossible

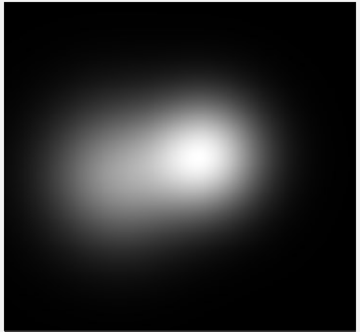


height spacing





higher intensity of the left light source



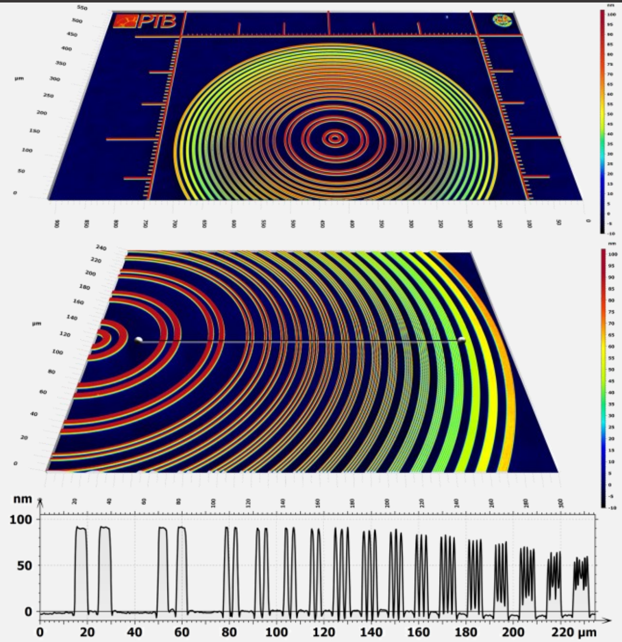
higher intensity of the right light source

- structures which reflect light may be located on different height levels
- different height levels may enable the separation of structures below the resolution limit
- theoretical consideration based on optical resolution and point density about the lateral system resolution can be confirmed with practical tests

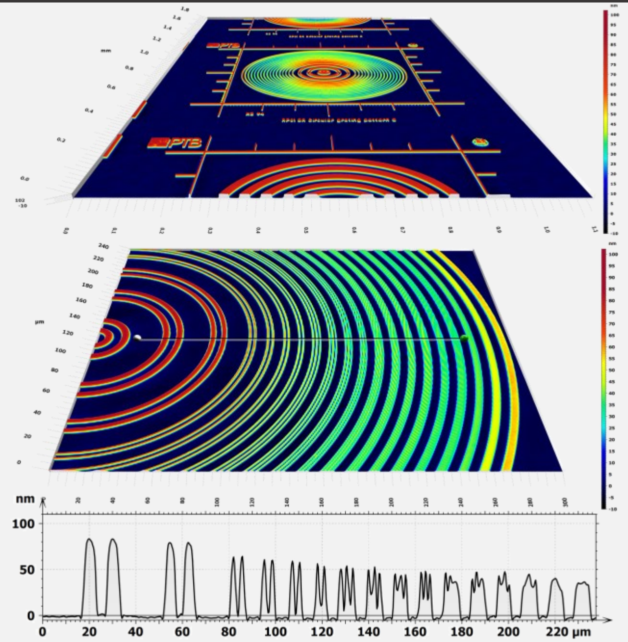
smart WLI

practical tests of the system resolution

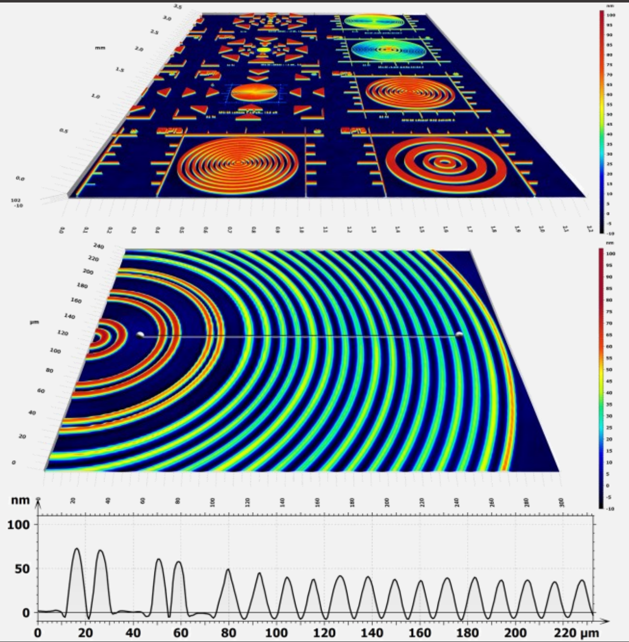
smartWLI compact, 20x objective



smartWLI compact, 10x objective



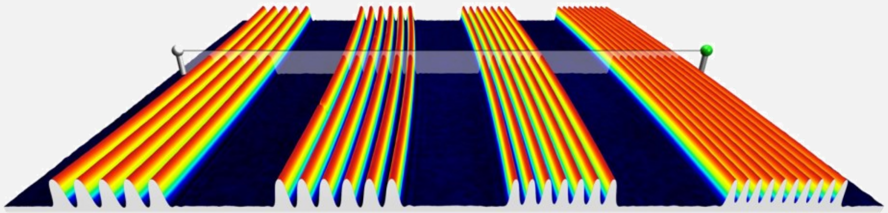
smartWLI compact, 5x objective



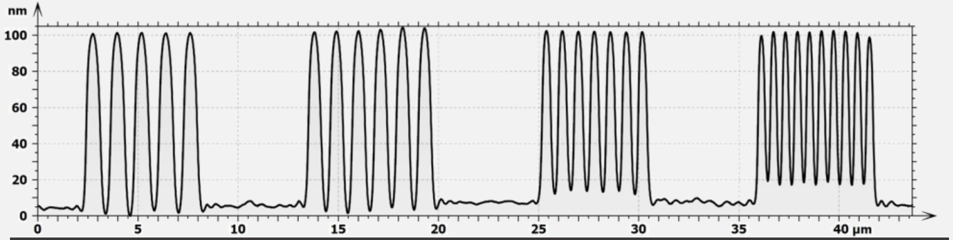
lateral period limit D_{LIM} (defined in ISO 25178-604 – drop of the measured amplitude of sinus structures as function of the wavelength to 50%) for the smartWLI compact with 2.3 MP camera

magnification factor	**2.5x**	**5x**	**10x**	**20x**	**50x**	**100x**
point density [µm]	3.8	1.9	0.96	0.48	0.19	0.1
D_{LIM} / µm	10	5	2.5	1.25	0.8	0.5

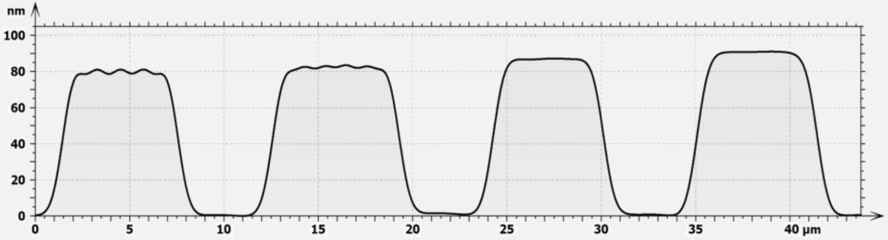
comparison to tactile measurements



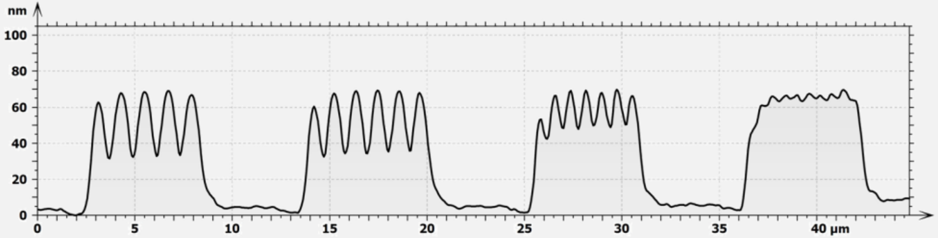
PTB resolution standard, nominal sinus height: 100 nm



smartWLI nanoscan, 100x objective
optical resolution = 0.27 µm, point density = 0.03 µm



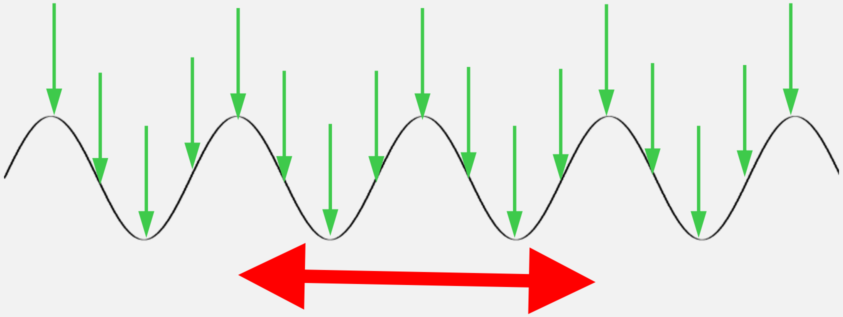
tactile measurement (simulation, without system noise and tactile damages)
tip diameter = 4 µm, high pass filter λs = 2.5 µm



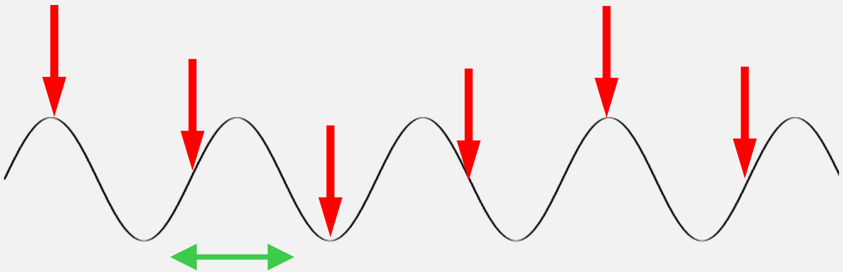
smartWLI compact, 50x objective
optical resolution = 0.48 µm, point density = 0.2 µm

The measured structure amplitude of the sinus structures highly depends on the resolution of the measuring system and the used objective. The effect increases with decreasing structure size. Depending on the real object structures and the measuring task, the optical profiler requires to provide significantly higher resolution than the surface feature structures to be analysed. Furthermore, the observed area of interest has to be selected such that several relevant structures or waves can be evaluated.

sampling theorem / optical resolution



point density good / optical resolution too bad



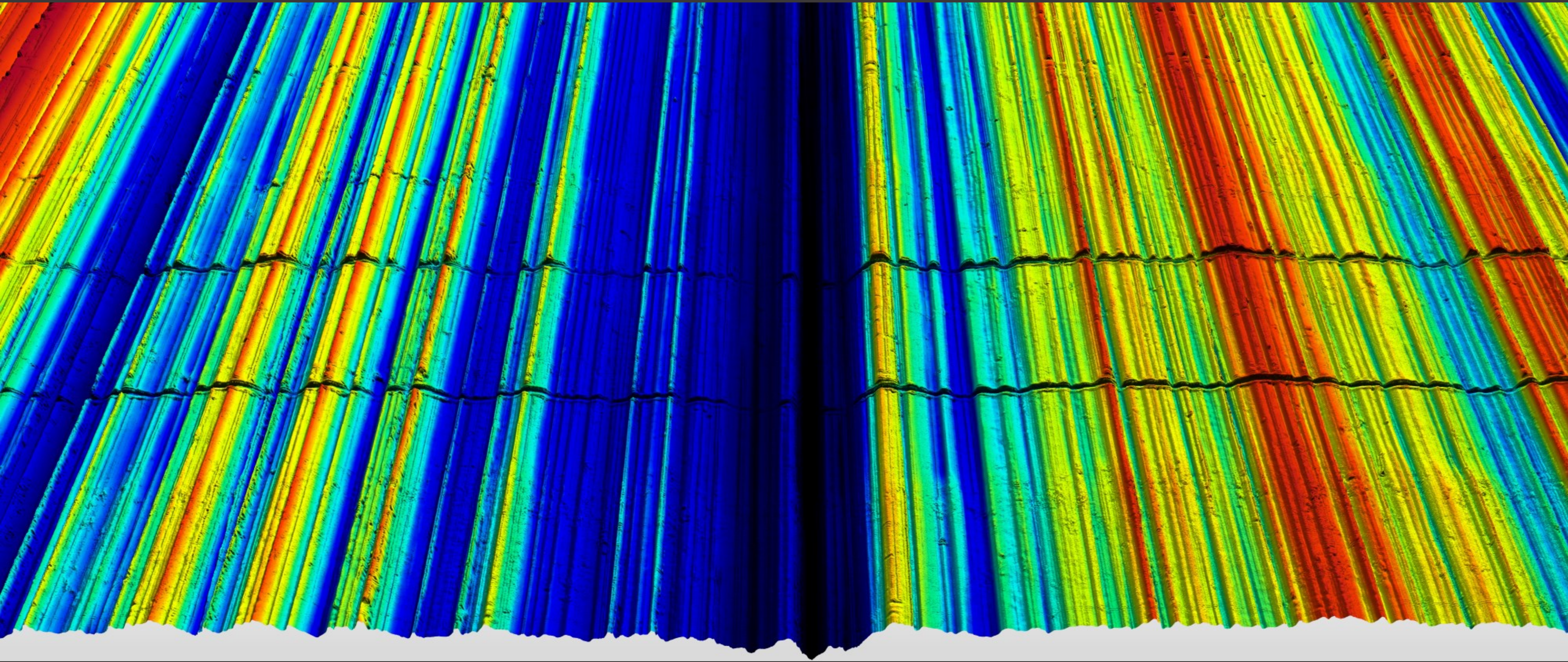
point density too bad / optical resolution ok

practical test of the smartWLI compact with 2.3 MP camera

- the resolution of the optical profiler can be limited from the point density and/or the optical resolution
- for one and the same sensor the situation depends from the used objective
- the reason is the not linear relation from objective magnification and optical resolution
- while the point density getting from the 2.5x objective to the 100x objective 40 times higher the optical resolution get only 10.7 times higher

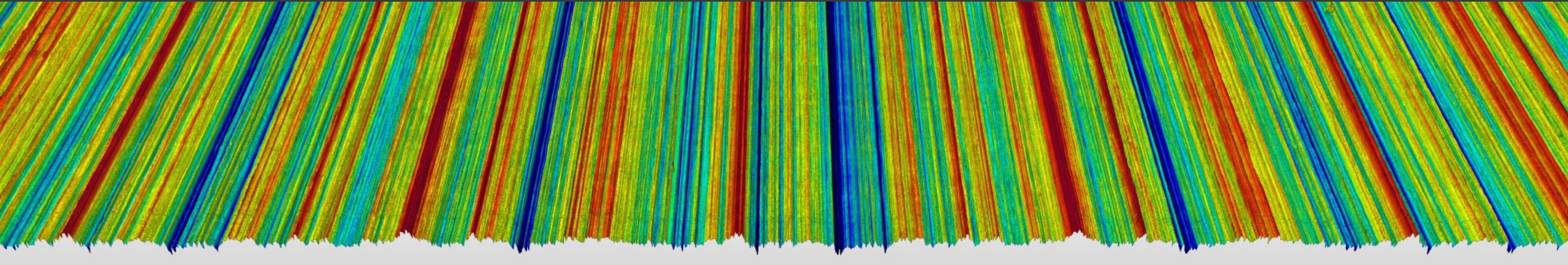
smartWLI

scratches of an stylus instrument on an roughness standard

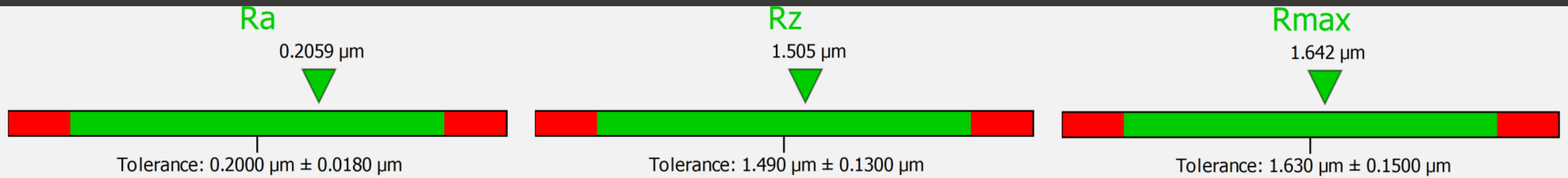


Stylus measuring instruments use a static force of 0.75 mN on the stylus tip with a radius < 2 µm to hold the tip on the surface while performing the scanning process.
This leads to measurable scratches on the measurand. A bigger tip radius will reduce the system resolution.
Using non-tactile optical coherence scanning interferometer demonstrates the limits of tactile measurements while providing the resolution for the visualization of such small damages.

smartWLI correct measurement of tracible roughness standards



Halle – KNT 4058/01 Nr. 7413 / 2015-12
certified surface standard



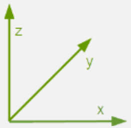
correct measurement of surface roughness:

- profile roughness measurements are originally standardized for stylus instruments
- even using optical high performance profilers certain rules of the ISO standards have to be respected to get correct measuring results
- ISO 4288: here for nonperiodic profiles with Ra 0.1 … 2 µm:
  - sampling length and cut off high pass filter: 0.8 mm
  - evaluation length: 4 mm
- ISO 3274: here for nonperiodic profiles with Ra 0.1 … 2 µm:
  - max. point distance: 0.5 µm
  - stylus tip radius: 2 µm (translated for optical profilers: optical resolution should be better than 2 µm)
  - cut off low pass filter: 2.5 µm

conclusions for optical profilers:

- the combined specification of ISO 4288 and ISO 3274 regarding point density and profile length require the generation of profiles with at least 8000 measuring points
- since smartWLI systems cannot provide 8000 measuring points in a single scan, multiple profile lines within the given AOI or multiple scans and stitching are required to fulfil the specification of ISO 4288 and ISO 3274
- one of the specific advantage of the smartWLI systems is the ability to scan larger areas with high resolution in a short measuring time

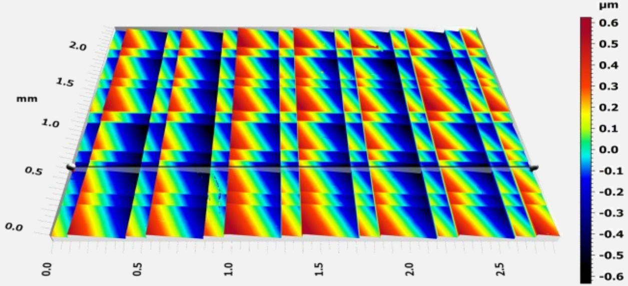
smartSTITCH perfect scans of larger areas

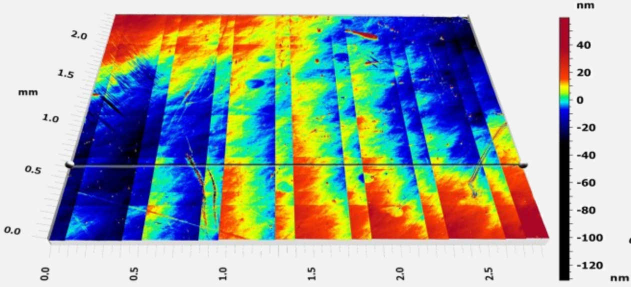


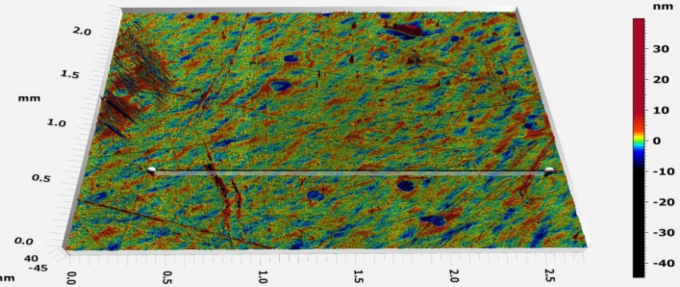
feature	flatness	straightness	pitch	yaw	technology
sensor	< 1 nm	< 1 nm	single µrad	single µrad	optics
positioning system	>> 1 µm	>> 1 µm	>> 10 µrad	>> 10 µrad	mechanics

smartSTITCH – the software for optimized stitching results on super smooth optical and semiconductor surfaces:

- mechanical positioning systems cause very small height and angle differences of the coordinate systems for every single scan
- these errors cause visible stitching artefacts
- height compensation using overlapping zones are available in many software evaluation packages like MountainsMap® to reduce the effect of errors
- for typical roughness measurements on machined surface with roughness values over 10 nm, the height compensation is in general acceptable
- even though eliminating some stitching errors, problems may stay visible:
    - using objectives with a lower magnification
    - on smooth surfaces e.g., optics, semiconductors, polished or diamond turned metal surfaces
- smartSTITCH compensates not only height but also angular errors, and provides much better results







stitching without error compensation

stitching with height compensation (MountainsMap®)

smartSTITCH with height and angular compensation