HANDS-ON SESSION
Optical Profilometry

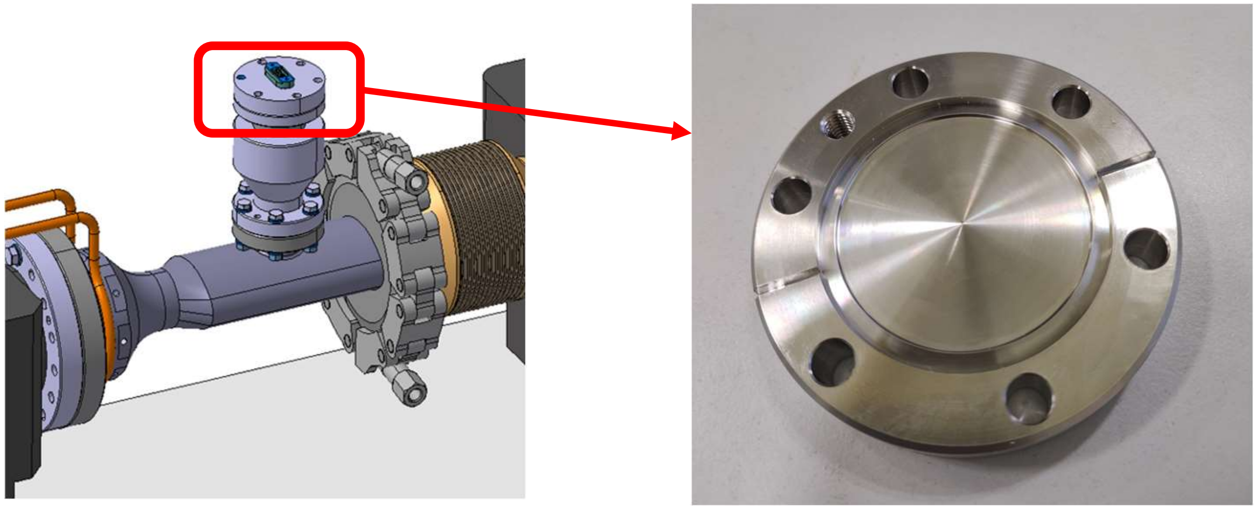
MECHANICAL & MATERIALS ENGINEERING
FOR PARTICLE ACCELERATORS AND DETECTORS

Welcome!

- The purpose of this presentation is to get acquainted with “surface roughness” and its optical measurement, and to **guide you through the steps** of the Hands-on session.

- If there are any questions, **you can consult one of the helpers** at any time and ask for information.

What will we measure?

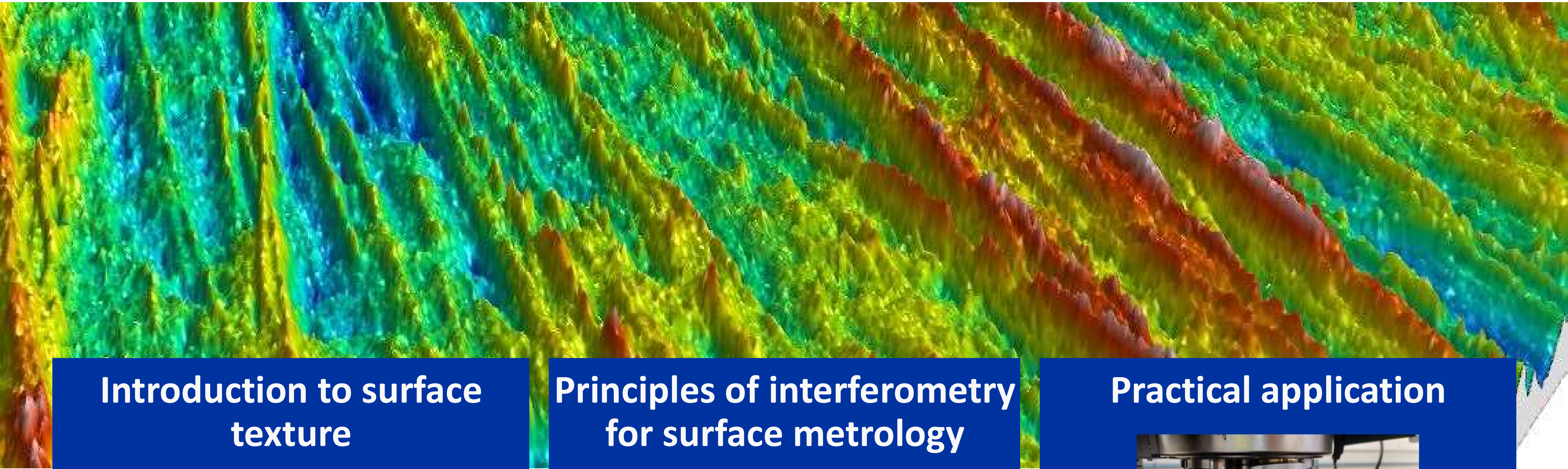


Roughness of UHV blank flange

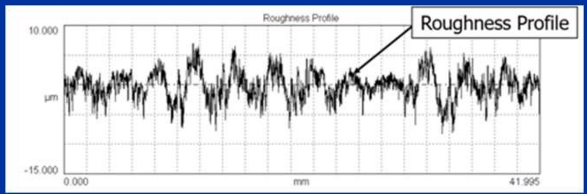
How will we measure it?

- **Tabletop optical profilometer**
- **Vertical Scanning Interferometry (a.k.a. White Light Interferometry)**

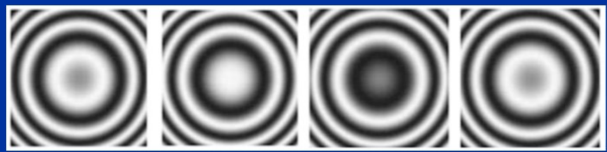
Hands-on session – Optical Profilometry



Introduction to surface texture



Principles of interferometry for surface metrology



Practical application

Introduction to surface texture

Introduction to surface texture

- Irregularities of engineered surfaces
- Definitions
- Arithmetic Mean Roughness
- Measurement methods

Irregularities of engineered surfaces

- **Intrinsic and characteristic of all manufacturing processes**
- **Influence on:**
  - Surface function
  - Aesthetics (touch & feel, visual)

Definitions

- **Surface profile**

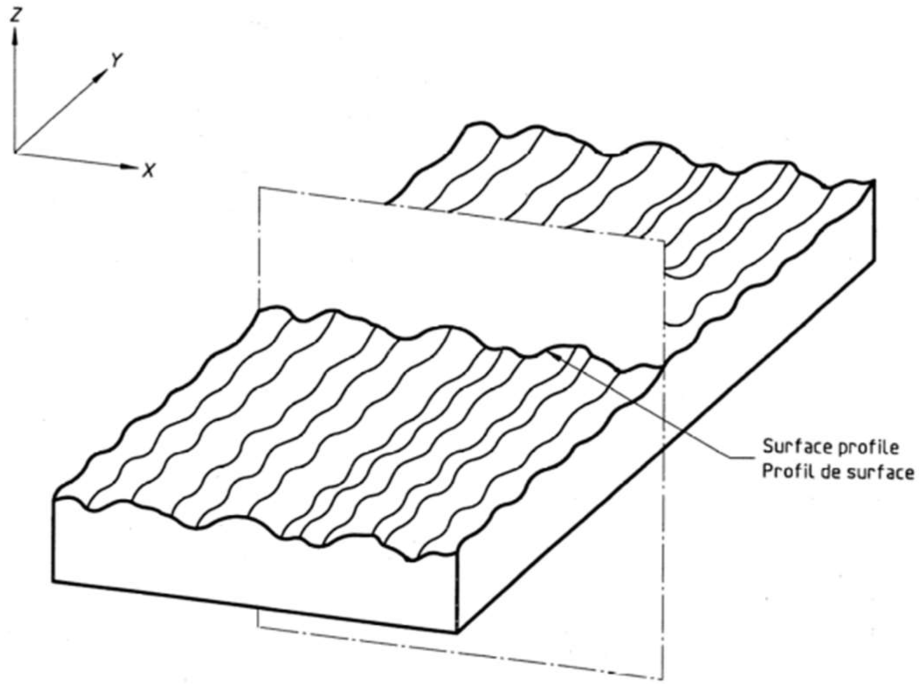
ISO 4287*

Profile that results from the intersection of the *real surface* by a specified plane

- A planar coordinate system is defined, such that:

$$SP \overset{\text{def}}{=} z = f(x)$$

- The plane normal generally lies parallel to the surface in a *suitable* direction

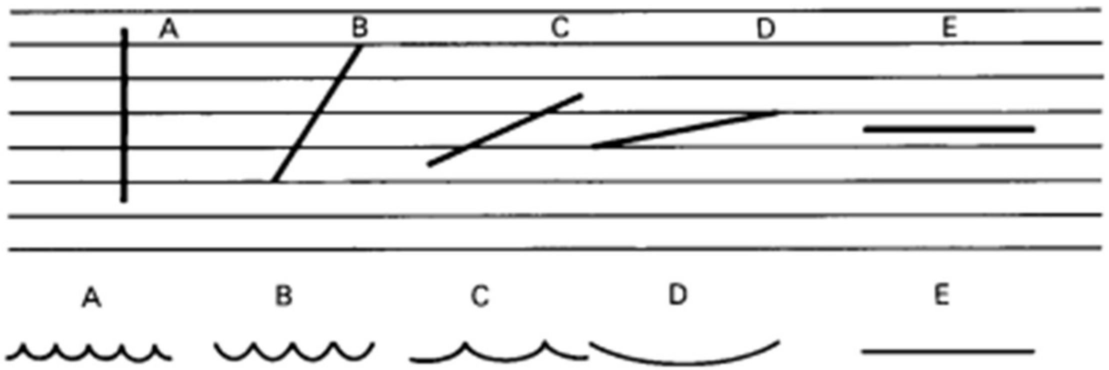


Definitions

- **Lay**

  Direction of the predominant surface pattern

  - Derives from production process

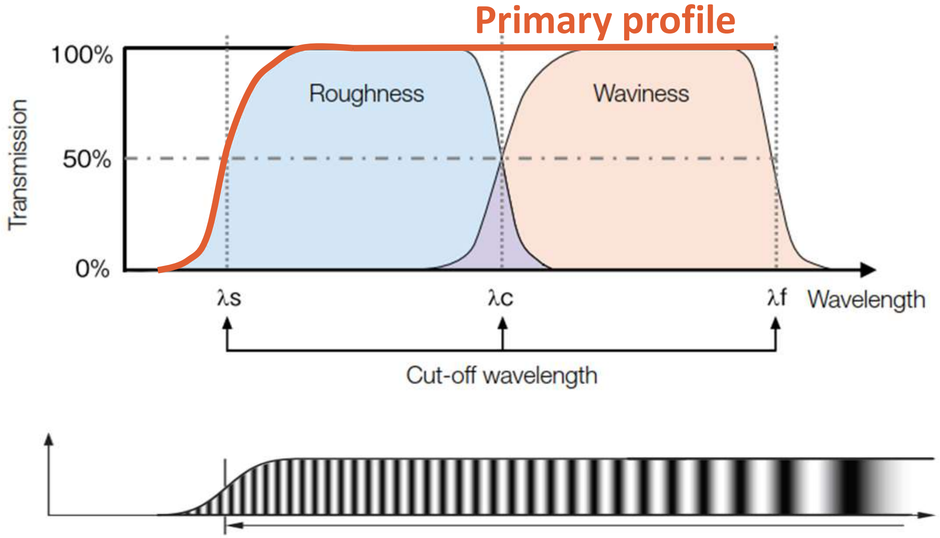


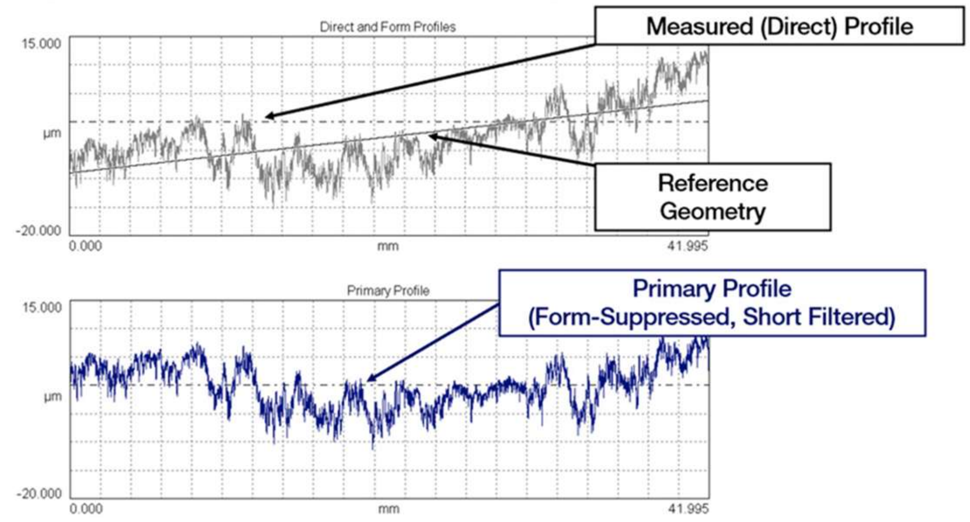
Definitions

- **Primary profile** ISO 3274

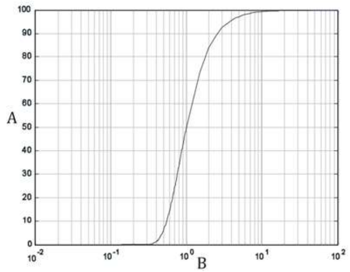
  Surface profile after application of the *short wavelength filter* λ_s. (low-pass filter)

  - Note: form is removed as well (e.g. « tilt »)





Filtration – Gaussian filters ISO 16610-61



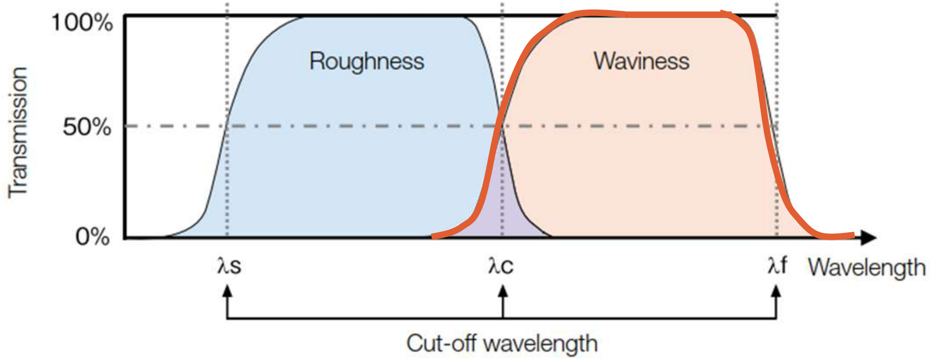
$$\frac{a_1}{a_0} = H(\lambda|\lambda_c) = \exp\left[-\pi\left(\alpha\frac{\lambda_c}{\lambda}\right)^2\right]$$

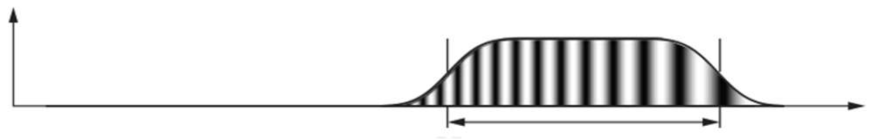
Long wave transmission function

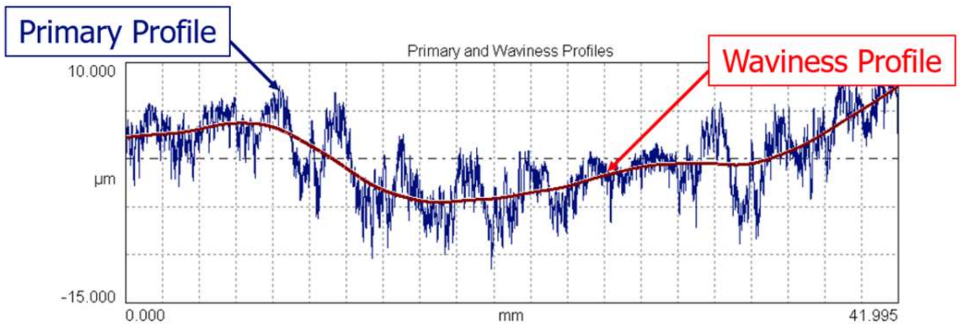
Definitions

- **Waviness profile** ISO 4287

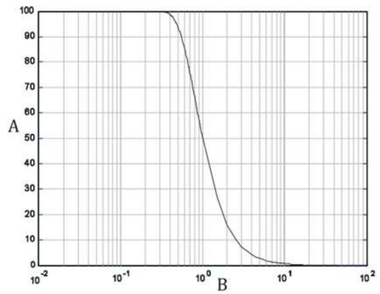
  Primary profile after application of the *short wavelength filter* λ_c (low-pass filter) and *long wavelength filter* λ_f (high-pass filter).







Filtration – Gaussian filters ISO 16610-61



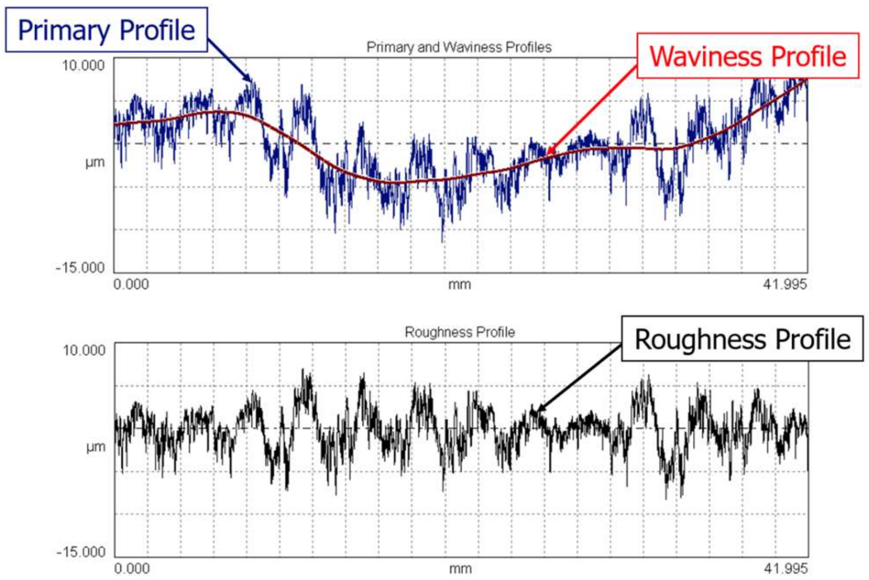
$$\frac{a_2}{a_0}=1-\frac{a_1}{a_0}=1-H(\lambda|\lambda_c)=1-\exp\left[-\pi\left(\alpha\frac{\lambda_c}{\lambda}\right)^2\right]$$

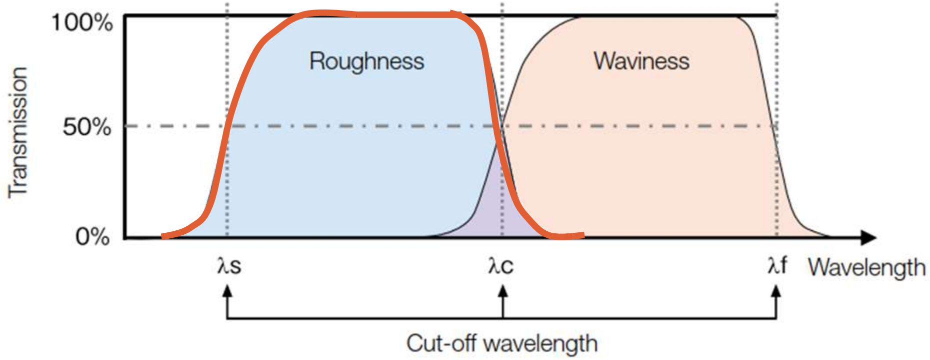
Short wave transmission function

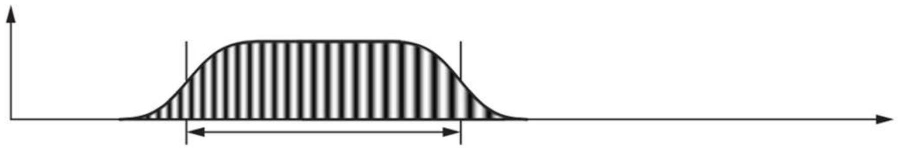
Definitions

- **Roughness profile** ISO 4287

  Primary profile after application of the *long wavelength filter* λ_c (high-pass filter).





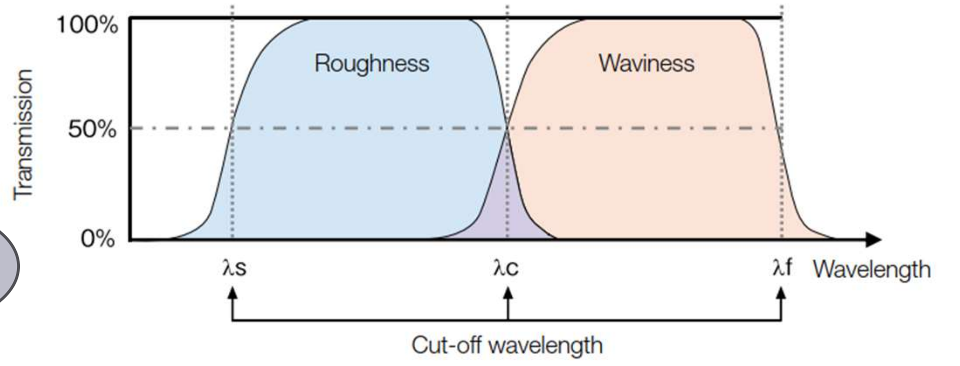


Selection of λ_c, λ_s ISO 4287 ISO 4288 ISO 3274

- *Function of roughness parameters*
- *Periodic vs. non-periodic patterns*

Periodic Profile	Non Periodic Profiles		Cut-off		Cut-off ratio	Evaluation Length	Stylus
Spacing Distance RSm (mm)	Rz (µm)	Ra (µm)	λc (mm)	λs (µm)	λc/λs	Lm (mm)	Radius (µm)
>0.013-0.04	to 0.1	to 0.02	0.08	2.5	30	0.4	2
>0.04-0.13	>0.1-0.5	>0.02-0.1	0.25	2.5	100	1.25	2
>0.13-0.4	>0.5-10	>0.1-2	0.8	2.5	300	4	2 (5 @ Rz> 3µm)
>0.4-1.3	>10-50	>2-10	2.5	8	300	12.5	5 or 2
>1.3-4.0	>50	>50	8	25	300	40	10, 5 or2

Definitions



- **Sampling length (lp, lw, lr)** ISO 4287

  Length in x direction used for identifying profile irregularities

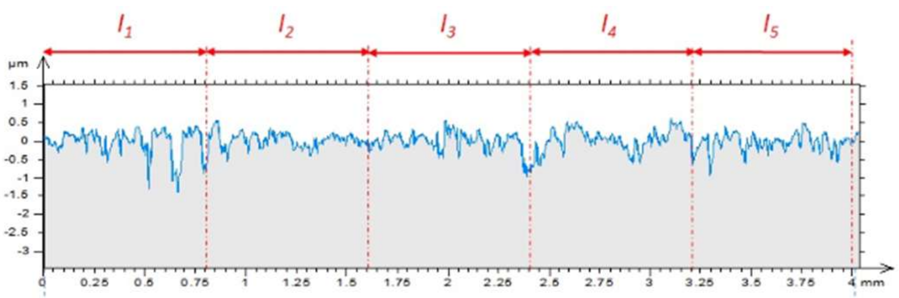
  - For roughness, lr = λ_c

ISO 4287 ISO 4288 ISO 3274

Periodic Profile	Non Periodic Profiles		Cut-off		Cut-off ratio	Evaluation Length	Stylus
Spacing Distance RSm (mm)	Rz (µm)	Ra (µm)	λc (mm)	λs (µm)	λc/λs	Lm (mm)	Radius (µm)
>0.013-0.04	to 0.1	to 0.02	0.08	2.5	30	0.4	2
>0.04-0.13	>0.1-0.5	>0.02-0.1	0.25	2.5	100	1.25	2
>0.13-0.4	>0.5-10	>0.1-2	0.8	2.5	300	4	2 (5 @ Rz> 3µm)
>0.4-1.3	>10-50	>2-10	2.5	8	300	12.5	5 or 2
>1.3-4.0	>50	>50	8	25	300	40	10, 5 or2

- **Evaluation length** ISO 4287

  5 times the sampling length



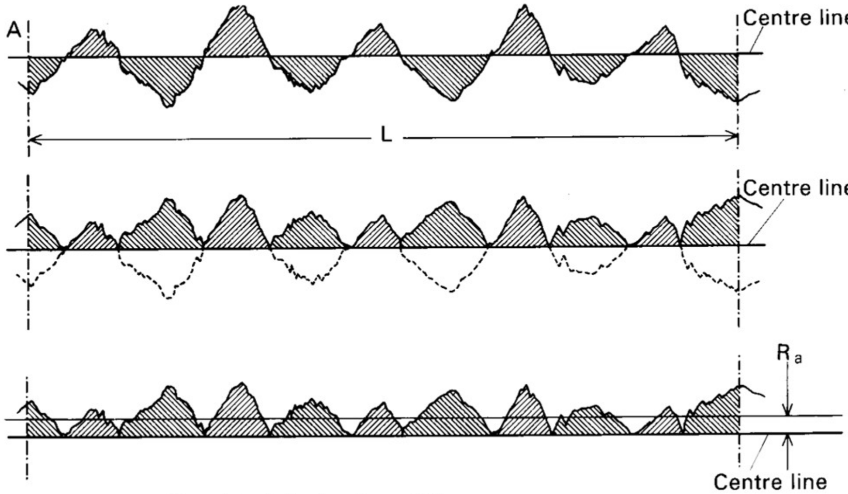
Arithmetic mean roughness Ra

ISO 4287

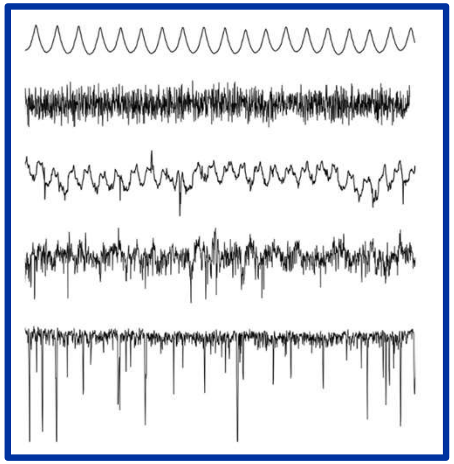
Ra is the **arithmetic mean** of the absolute ordinate values R(x) of the roughness profile, evaluated within the sampling length.

$$Ra = \frac{1}{l}\int_0^l |\boldsymbol{R}(x)|dx$$

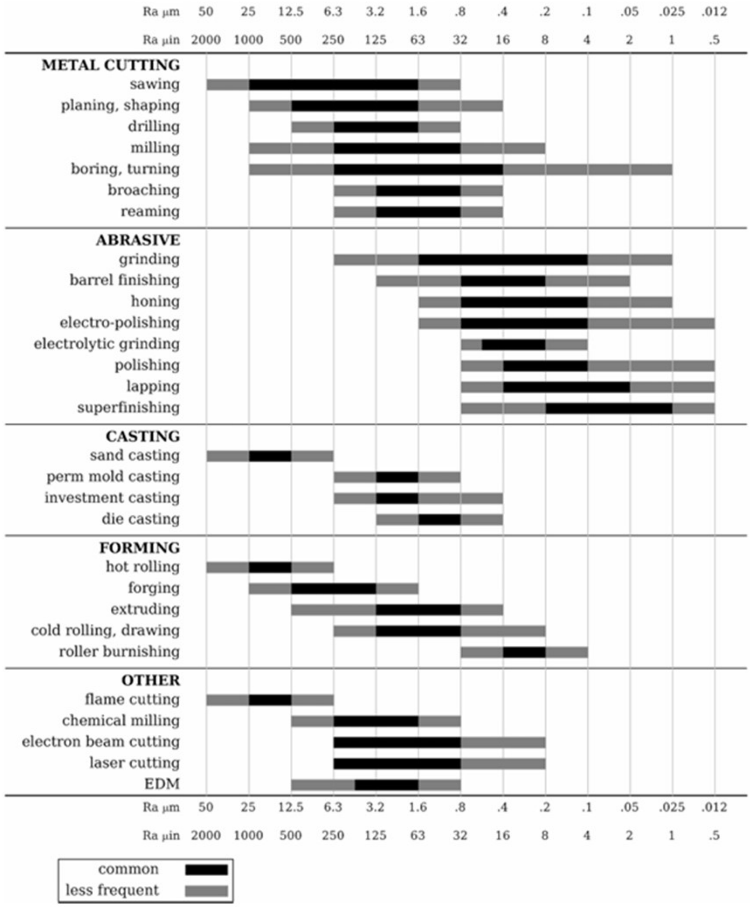
- Can vary considerably without affecting functionality → usually, only a maximum Ra is specified
- **Varies considerably with the orientation of the measurement plane**
- Does not provide any information about the the shape of irregularities
- It is relatively insensitive to big peaks/valleys
- Surfaces with very different profiles can have the same Ra
- Most commonly used for historical reasons and good correlation with typical machining processes
- Other profile parameters exist, we will not examine them here

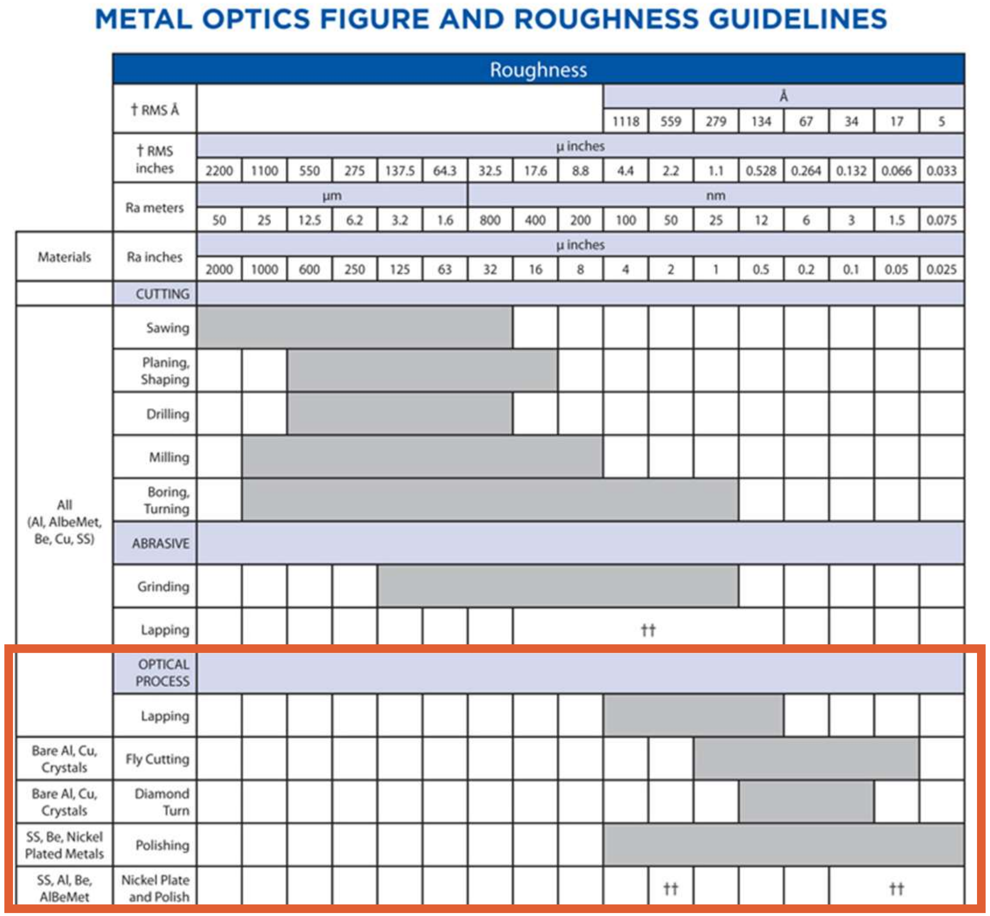


Graphical derivation of R_a



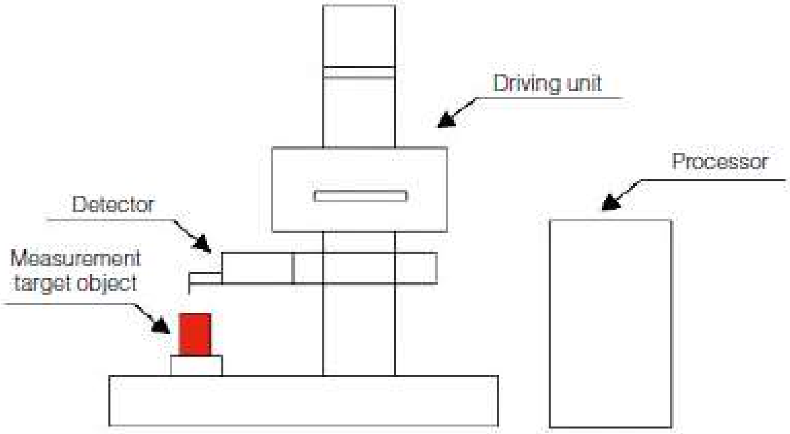
Typical values of Ra

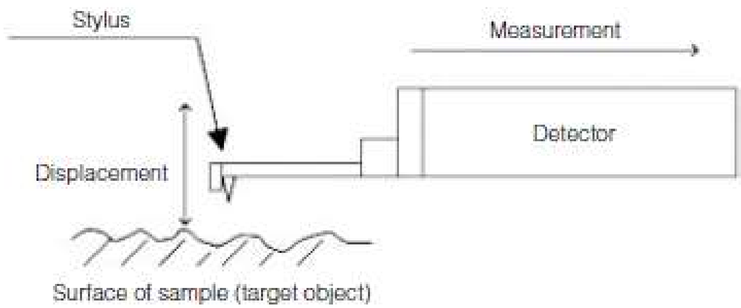


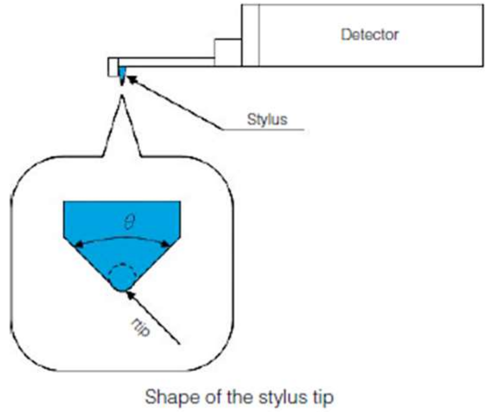


Measurement methods

Contact (stylus)



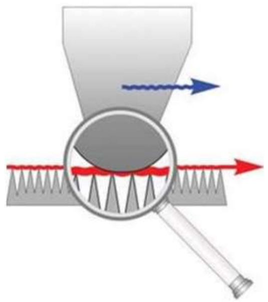




- Straightforward, reproducible measurement
- Simple measurement over long distances and height variations
- Portable
- Long track record of use
- Characteristics are standardized →

ISO 3274

- Can damage the sample
- Stylus wear
- Mechanical filter, vibrations
- Only profle parameters (2D)



λc mm	λs µm	$\lambda c/\lambda s$	r_{tip} max. µm	Maximum sampling spacing µm
0,08	2,5	30	2	0,5
0,25	2,5	100	2	0,5
0,8	2,5	300	2 *)	0,5
2,5	8	300	5 **)	1,5
8	25	300	10 **)	5

Measurement methods

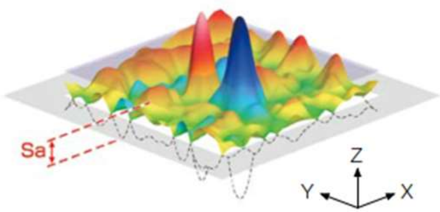
Non-Contact

- Interferometric methods
- Chromatic Confocal Profiling
- Autofocus sensor
- Laser triangulation
- …

- Do not damage the sample
- Better vertical and lateral resolutions
- Capable of measuring areal parameters (3D)

- Complex use
- Reproducibility (raw data, processing)

$$Sa = \frac{1}{A}\iint_A |Z(x,y)|\,dxdy$$



Principles of interferometry for surface metrology

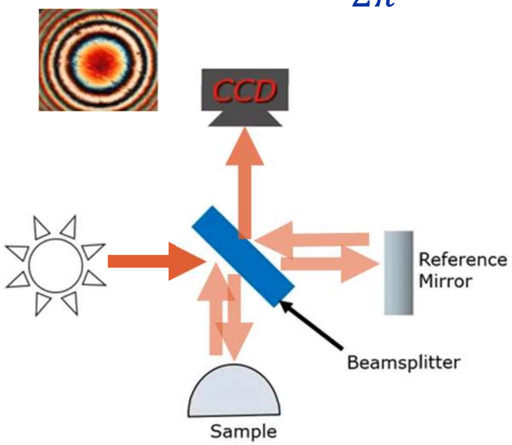
Principles of interferometry for surface metrology

- **Principles of interferometry**
- **Vertical Scanning Interferometry (VSI)**
- **Objective specifications**

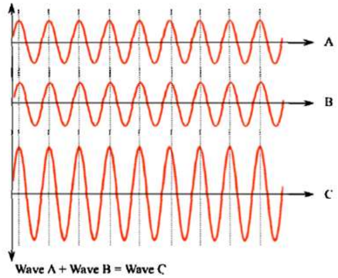
Principles of interferometry

An **interferometer** divides a light beam from a single **coherent** source in two **wavefronts** (reference + test) and recombines them to create an **interference pattern**. The difference in paths (**Optical Path Difference, OPD**) can be determined by examining the **interferogram.**

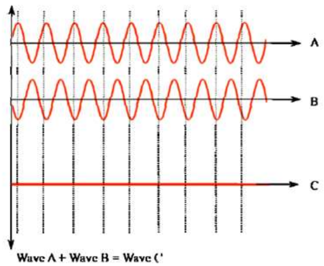
$$OPD = \frac{\lambda}{2\pi}\Delta\varphi$$

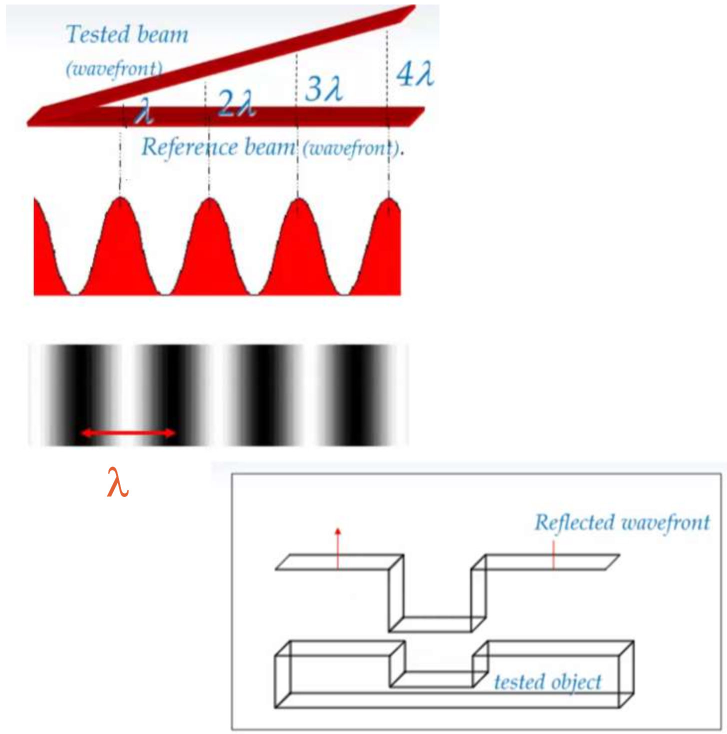


Constructive interference



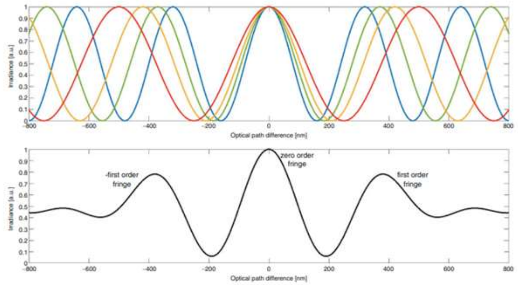
Destructive interference

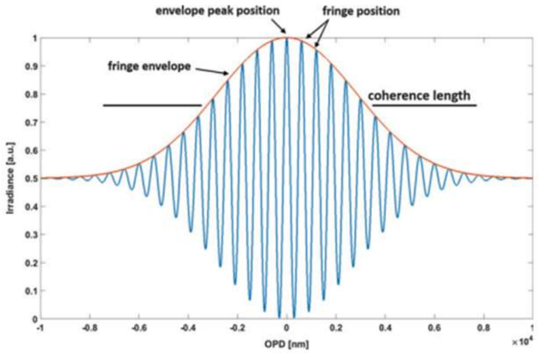


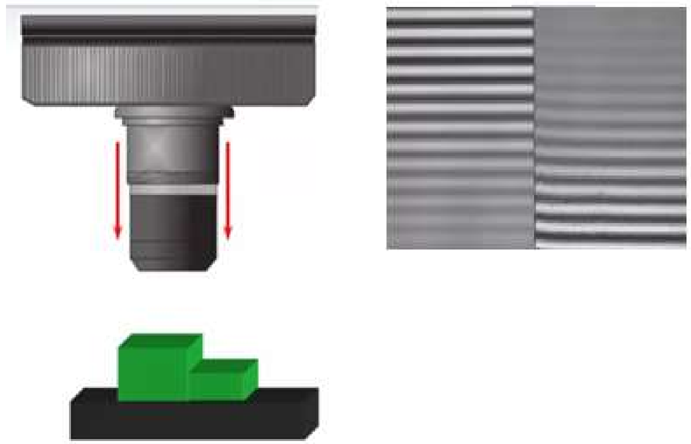


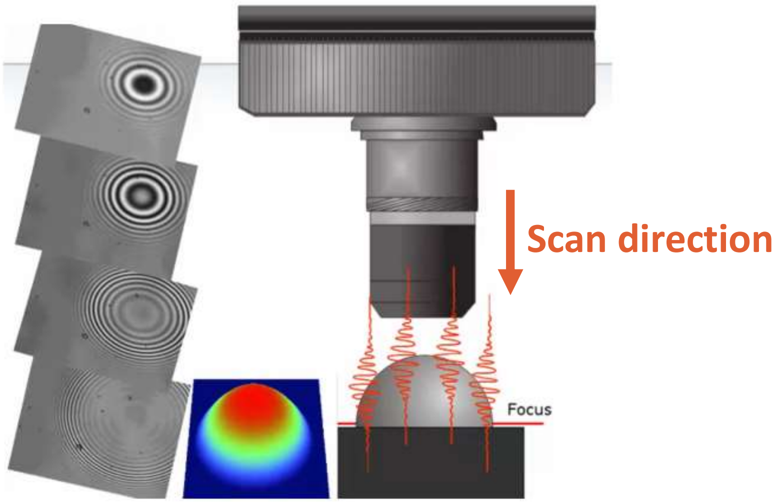
Vertical Scanning Interferometry (VSI)

- **White light illumination**
- **Rough, tall, discontinuous surfaces**
- **μm vertical resolution**
- **Large scanning distance (mm)**









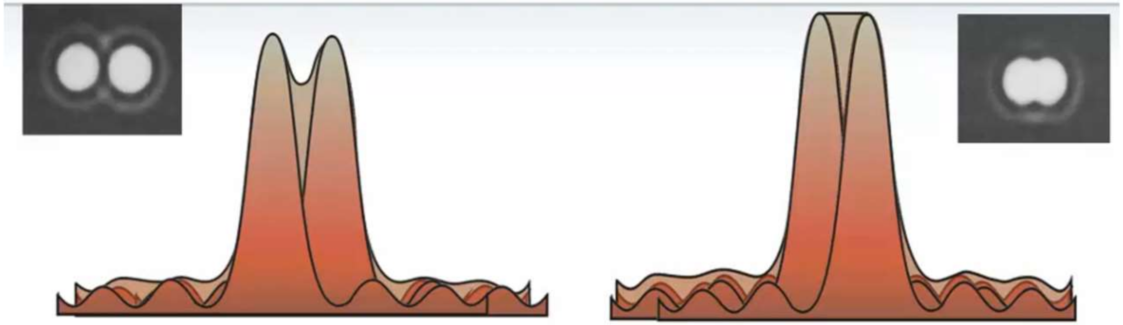
Objective specifications

- **Bigger magnification → Smaller Field Of View (FOV), better resolution**
- **Bigger working distance → less collision risk, bigger Z measuring range**
- **Bigger zoom → smaller FOV, better resolution**

Objective (Magnification[1])	2.5X		5X	
Working Distance (mm)	3.5		6.7	
Numerical Aperture	0.07		0.12	
Max Slope on Shiny Surfaces (deg)[2]	3		5.5	
Max Slope on Rough Surfaces (deg)[3]	62		65	
Optical Resolution (μm)[4]	3.8		2.2	
Tallest Sample: with XY Stage (mm)	340		340	
Tallest Sample: without XY Stage (mm)	397		397	
Vertical Resolution (nm)[5]	<0.15		<0.15	
	FOV (X by Y) (mm)	Spatial Sampling (μm)	FOV (X by Y) (mm)	Spatial Sampling (μm)
Standard Camera				
0.55x zoom	4.6 x 3.5	7.2	2.3 x 1.7	3.6
0.75x zoom	3.4 x 2.5	5.3	1.7 x 1.3	2.6
1.0x zoom	2.5 x 1.9	4.0	1.3 x 1.0	2.0
1.5x zoom	1.7 x 1.3	2.6	0.8 x 0.6	1.3
2.0x zoom	1.3 x 1.0	2.0	0.6 x 0.5	1.0

Objective specs - Optical resolution

Objective (Magnification[1])	2.5X
Working Distance (mm)	3.5
Numerical Aperture	0.07
Max Slope on Shiny Surfaces (deg)[2]	3
Max Slope on Rough Surfaces (deg)[3]	62
Optical Resolution (µm)[4]	3.8
Tallest Sample: with XY Stage (mm)	340
Tallest Sample: without XY Stage (mm)	397
Vertical Resolution (nm)[5]	<0.15



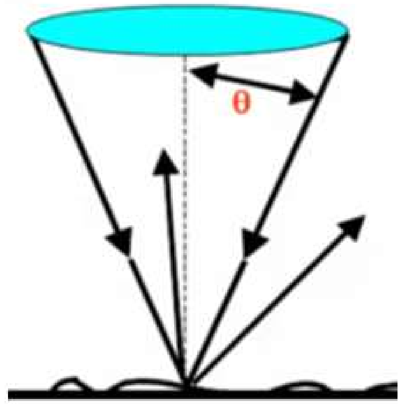
- **Rayleigh criterion**
- $Res = 0.61\frac{\lambda}{NA}$

Sparrow criterion

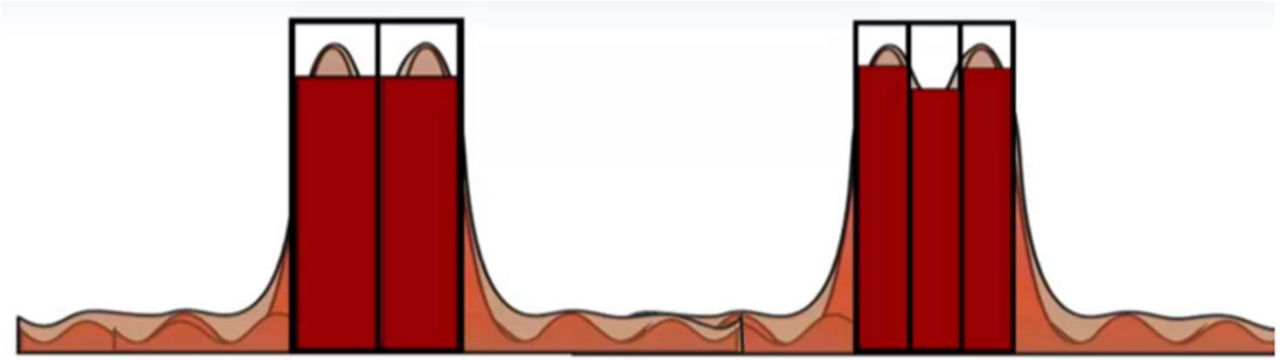
$$Res = 0.47\frac{\lambda}{NA}$$

NA is Numerical Aperture

$$NA = sin(\vartheta)$$



Objective specs - Lateral resolution limits



System is limited by detector

Larger pixels limit image delivered by optics

System is limited by optics

More or smaller pixels do not help in resolving smaller features

Objective (Magnification[1])	2.5X	
Working Distance (mm)	3.5	
Numerical Aperture	0.07	
Max Slope on Shiny Surfaces (deg)[2]	3	
Max Slope on Rough Surfaces (deg)[3]	62	
Optical Resolution (µm)[4]	3.8	
Tallest Sample: with XY Stage (mm)	340	
Tallest Sample: without XY Stage (mm)	397	
Vertical Resolution (nm)[5]	<0.15	
	FOV (X by Y) (mm)	Spatial Sampling (µm)
Standard Camera		
0.55x zoom	4.6 x 3.5	7.2
0.75x zoom	3.4 x 2.5	5.3
1.0x zoom	2.5 x 1.9	4.0
1.5x zoom	1.7 x 1.3	2.6
2.0x zoom	1.3 x 1.0	2.0

Practical Application

Practical application

- Introduction to ContourX profiler and Vision64 software
- Measurement of Ra on flange samples

ContourX-500

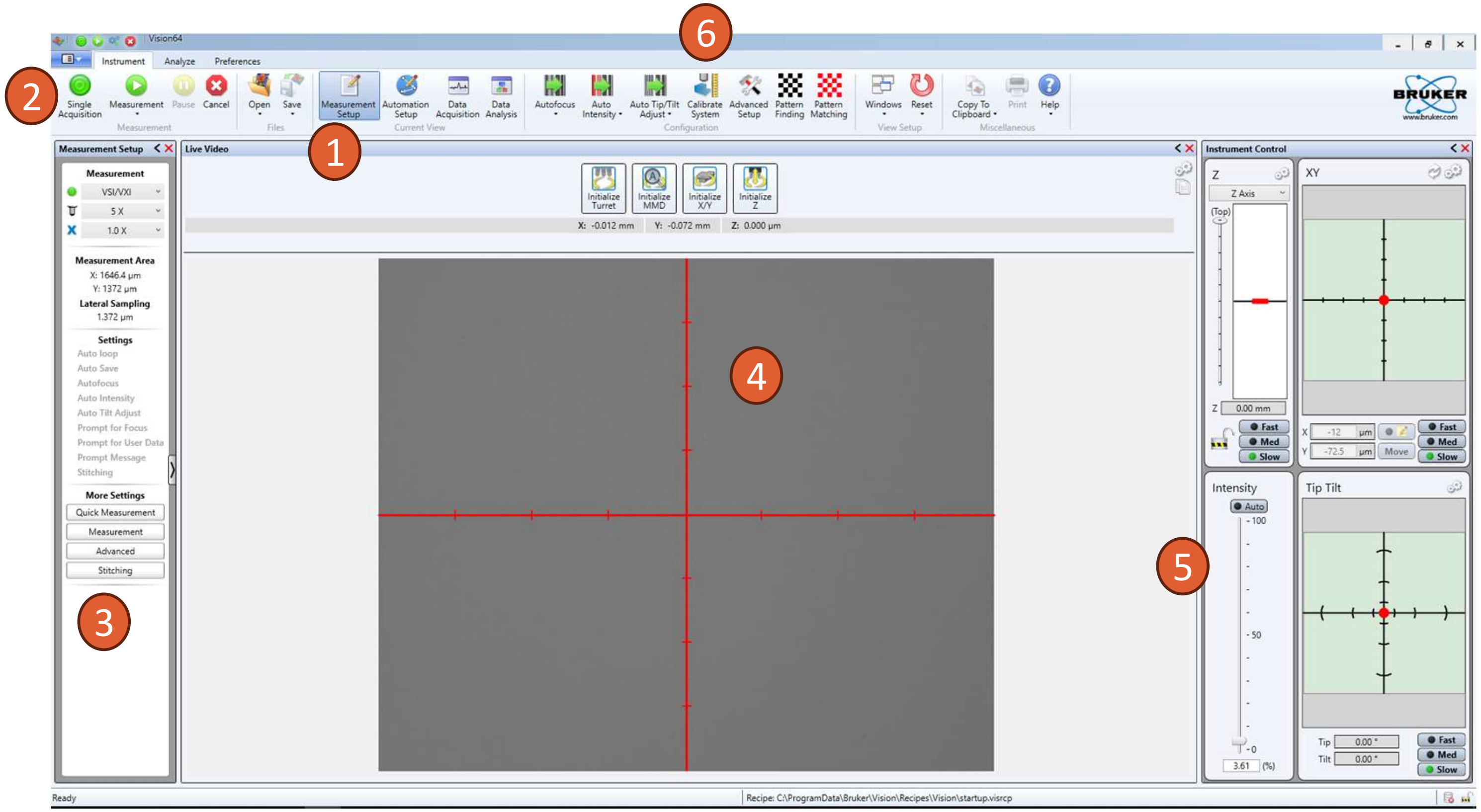
- Objective turret with 5x → 115x objectives
- Motorized head (Scanning in Z, rotations around X and Y to adjust parallelism between sample and reference)
- Motorized stage (translations in XY plane)

Control Box

1. **Z-axis fast mode button**
2. **Z-axis knob**
3. **Stage OR tip-tilt control joystick**
4. **High speed joystick button**
5. **Tip-tilt button**

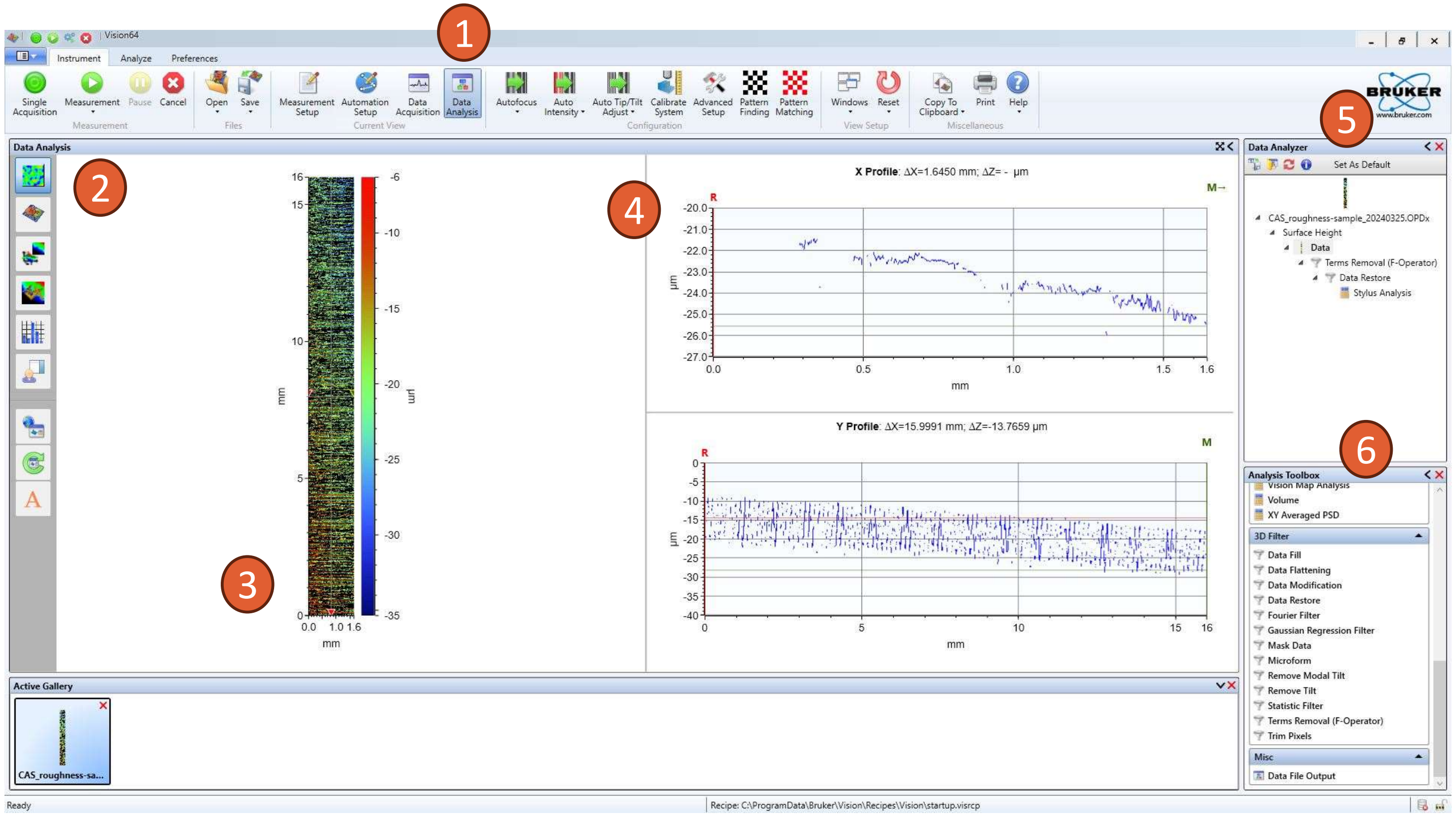
Vision64 interface – Measurement setup

1. Measurement setup icon
2. Measurement buttons (single/multiple)
3. Measurement setup tab
4. Live video feed
5. Intensity slider
6. Calibration icon



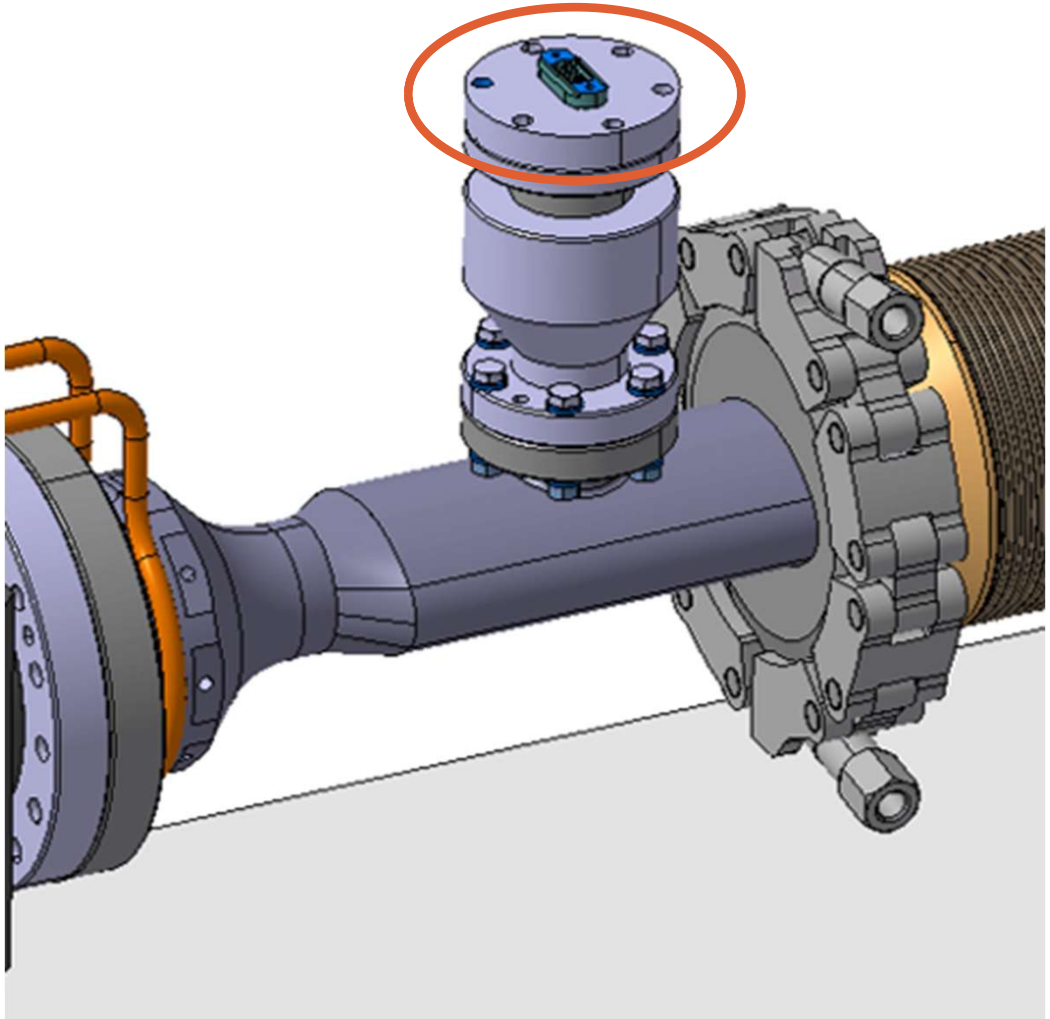
Vision64 interface – Data Analysis

1. Data Analysis button
2. Data Analysis window
3. 2D measurement view
4. Cross section profiles
5. Data Analyzer window
6. Analysis Toolbox
   - 3D filters
   - Analyses



Measurement of roughness

- **Purpose:** Measure Ra
- **Objective:** **TBD**
- **Technique:** VSI
- **Sample:** UHV blank flange

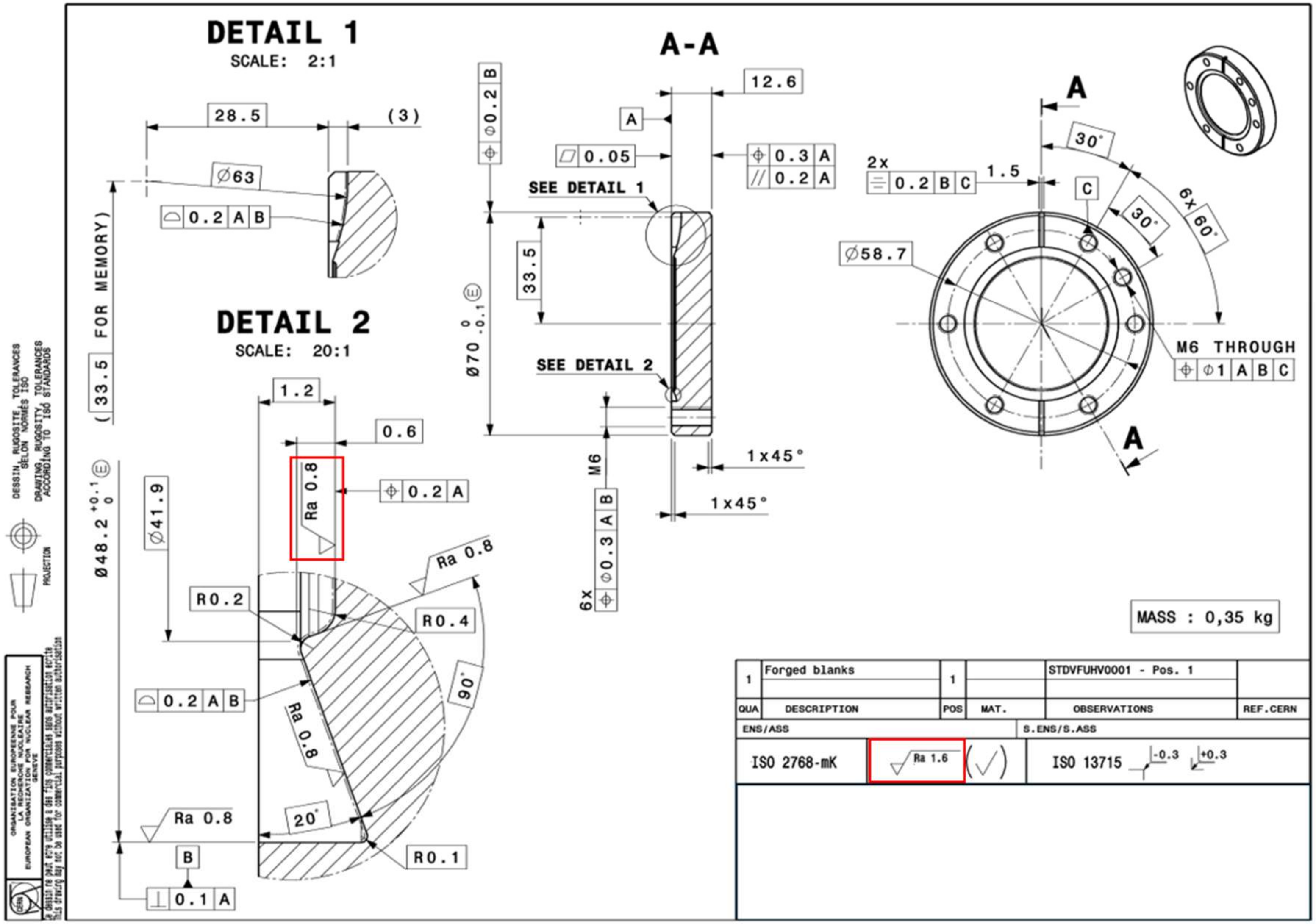


Measurement of roughness

Requirements

- General roughness on bolt circle area (priority measurement)
- Specific roughness on central surface (optional measurement)

The requirements specify the **maximum allowable Ra**.



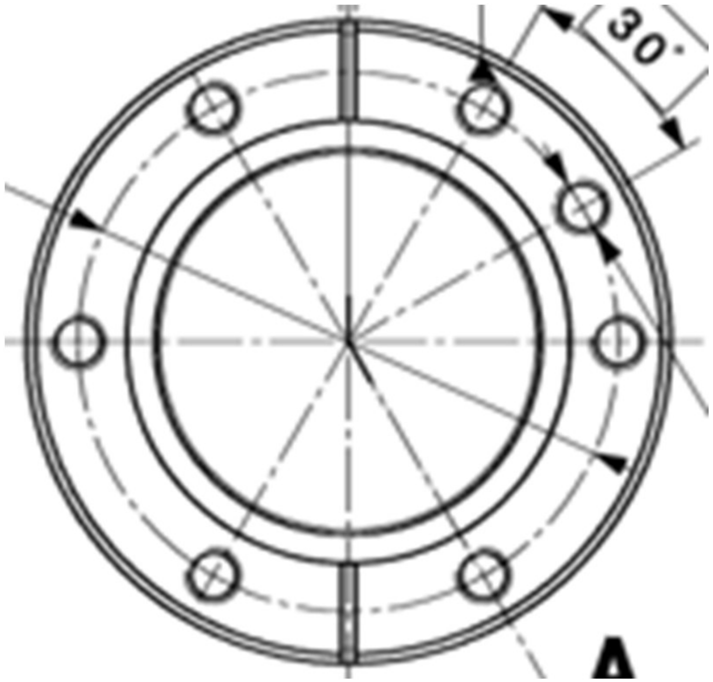
Measurement of roughness

- **Workflow**

1. Estimate roughness value using Rugotest viso-tactile comparator
   a. Identify machining process
   b. Select the appropriate measurement direction
2. Select appropriate evaluation parameters (cut-offs, sampling length, evaluation length)
3. Select suitable objective
4. Set up the measurement and perform the measurement
5. Process the data to obtain the numerical value of Ra
6. Compare the measurement result with the estimation of step 1
7. (optional) How is the value of Ra affected by measurement direction? Validate your hypothesis with a measurement.

Measurement of roughness

1. **Estimate roughness value using Rugotest viso-tactile comparator**
   - A. What is the manufacturing process?
   - B. What is the correct measurement direction in order to evaluate the maximum roughness?



Measurement of roughness

2. Select evaluation parameters

Based on the roughness value estimated at step 1, select the appropriate values for the following parameters:

- *long wavelength filter* λ_c =
- *short wavelength filter* λ_s =
- *Sampling length lr =*
- *Evaluation Length Lm =*

ISO 4287

ISO 4288

ISO 3274

Periodic Profile	Non Periodic Profiles		Cut-off		Cut-off ratio	Evaluation Length	Stylus
Spacing Distance RSm (mm)	Rz (µm)	Ra (µm)	λc (mm)	λs (µm)	λc/λs	Lm (mm)	Radius (µm)
>0.013-0.04	to 0.1	to 0.02	0.08	2.5	30	0.4	2
>0.04-0.13	>0.1-0.5	>0.02-0.1	0.25	2.5	100	1.25	2
>0.13-0.4	>0.5-10	>0.1-2	0.8	2.5	300	4	2 (5 @ Rz> 3µm)
>0.4-1.3	>10-50	>2-10	2.5	8	300	12.5	5 or 2
>1.3-4.0	>50	>50	8	25	300	40	10, 5 or2

Measurement of roughness

3. Select suitable objective

Select among the objectives in the next slide, considering the following criteria:

- The supplier measured roughness with a stylus instrument with a tip radius of 2 μm (as recommended by the standard). We need our results to be comparable in order to avoid acceptance disputes.
- For simplicity, limit the choice to 1.0 zoom
- In order to cover the full evaluation length, multiple measurement will be made and “stitched” together (check FOV dimensions!). Try to minimize the number of measurement required
- All things equal, an objective with longer working distance should be preferred, to avoid collisions.
- Motivate your choice.

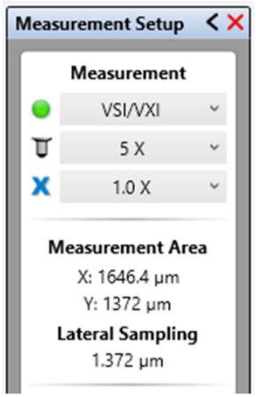
Measurement of roughness

3. Select suitable objective

Objective (Magnification[1])	2.5X		5X		5XL		10XBF		10X		20X		50X		100X		115X	
Design	Michelson		Michelson		Michelson		Brightfield		Mirau		Mirau		Mirau		Mirau		Mirau	
Working Distance (mm)	3.5		6.7		9.4		10.6		7.4		4.7		3.4		2.0		0.7	
Numerical Aperture (NA)	0.07		0.12		0.13		0.25		0.3		0.4		0.55		0.7		0.8	
Max Slope on Shiny Surfaces (deg)[2]	4		6.9		7.5		14.5		17.5		23.6		33.4		44.4		53.2	
Max Slope on Rough Surface (deg)[3]	62		65		65		NA		70		72		81		85		87	
Optical Resolution (μm)[4]	3.82		2.23		2.23		1.07		0.89		0.67		0.49		0.38		0.33	
Parfocal Distance (mm)	51.28		51.28		51.28		51.28		51.28		51.28		51.28		51.28		51.28	
Max Sample Height: ContourGT-X (mm)	101		101		101		101		101		101		101		101		101	
Max Sample Height: ContourX (mm)	95		95		95		95		95		95		95		95		95	
Max Sample Height: NPFLEX (mm)[5]	397		397		397		397		397		397		397		397		397	
Vertical Resolution (nm)[6]	0.01		0.01		0.01		0.01		0.01		0.01		0.01		0.01		0.01	
Bruker Part Number	831-760-20		831-209-20		831-170-20		831-149		831-182		831-124		831-759		831-382		831-489	
	FOV X by Y (mm)	Spatial Sampling (μm)	FOV X by Y (mm)	Spatial Sampling (μm)	FOV X by Y (mm)	Spatial Sampling (μm)	FOV X by Y (mm)	Spatial Sampling (μm)	FOV X by Y (mm)	Spatial Sampling (μm)	FOV X by Y (mm)	Spatial Sampling (μm)	FOV X by Y (mm)	Spatial Sampling (μm)	FOV X by Y (mm)	Spatial Sampling (μm)	FOV X by Y (mm)	Spatial Sampling (μm)
5MP High-Res. Camera: (1200x1000 array)[7]																		
0.55x Zoom	6.02x5.02	5.02	3.01x2.51	2.51	3.01x2.51	2.51	1.37x1.14	1.14	1.51x1.25	1.25	0.75x0.63	0.63	0.30x0.25	0.25	0.15x0.13	0.13	0.13x0.11	0.11
0.75x Zoom	4.42x3.68	3.68	2.21x1.84	1.84	2.21x1.84	1.84	1.00x0.84	0.84	1.10x0.92	0.92	0.55x0.46	0.46	0.22x0.18	0.18	0.11x0.09	0.09	0.10x0.08	0.08
1.0x Zoom	3.31x2.76	2.76	1.66x1.38	1.38	1.66x1.38	1.38	0.75x0.63	0.63	0.83x0.69	0.69	0.41x0.35	0.35	0.17x0.14	0.14	0.08x0.07	0.07	0.07x0.06	0.06
1.5x Zoom	2.21x1.84	1.84	1.10x0.92	0.92	1.10x0.92	0.92	0.50x0.42	0.42	0.55x0.46	0.46	0.28x0.23	0.23	0.11x0.09	0.09	0.06x0.05	0.05	0.05x0.04	0.04
2.0x Zoom	1.66x1.38	1.38	0.83x0.69	0.69	0.83x0.69	0.69	0.38x0.31	0.31	0.41x0.35	0.35	0.21x0.17	0.17	0.08x0.07	0.07	0.04x0.03	0.03	0.04x0.03	0.03

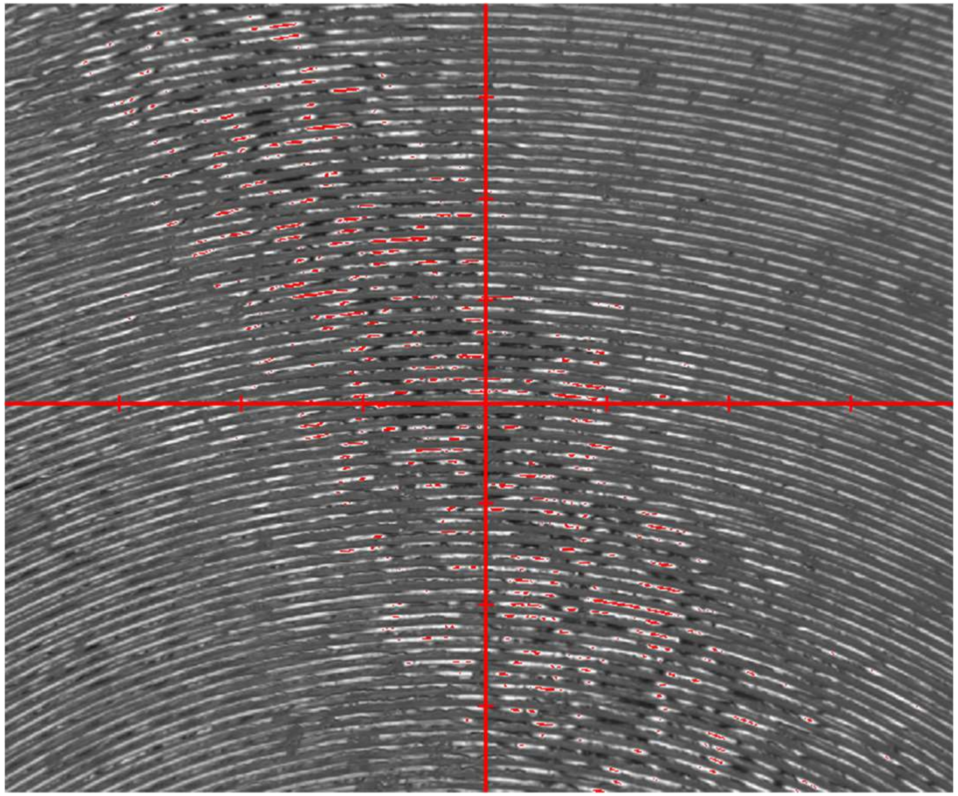
Measurement of roughness – step 4

1. Check measurement parameters:
   - VSI/VXI
   - **Selected objective**
   - 1.0x zoom
2. Place sample on XY stage
3. Bring sample under objective
4. Lower the objective close to working distance



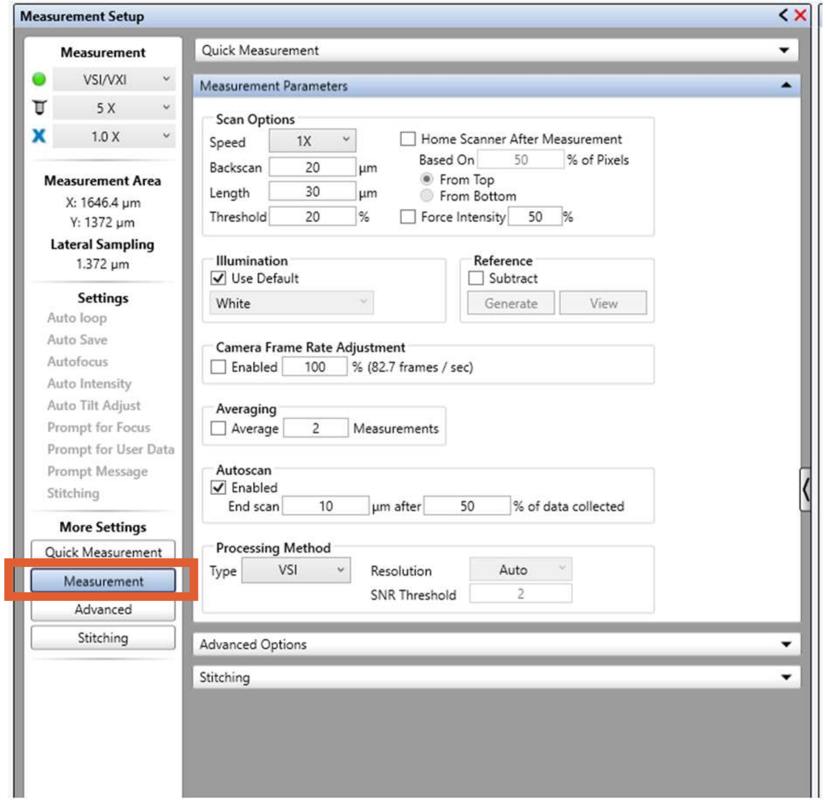
Measurement of roughness – step 4

5. Move sample so that the bottom of sample measurement area is below the objective
6. Find focus
7. Find fringes on video feed:
   a. Adjust intensity as needed
   b. Move objective in Z until fringes are visible on the video feed
   c. Use tip-tilt if necessary to orient the sample to the objective



Measurement of roughness – step 4

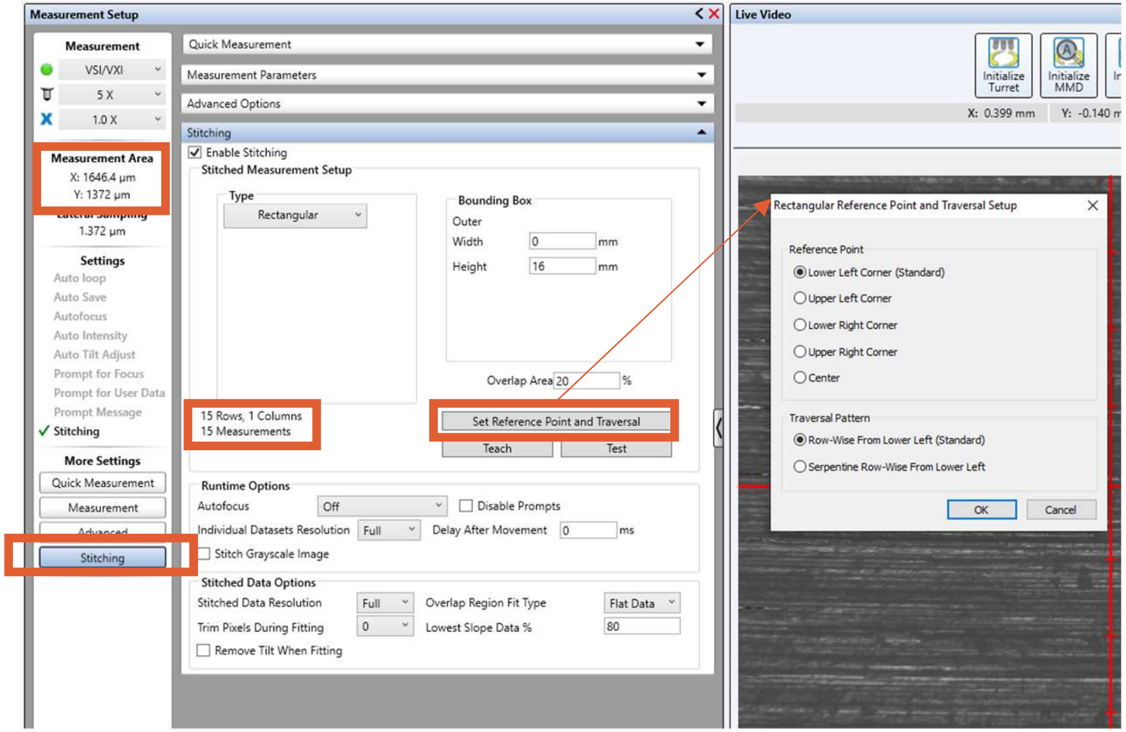
8. Open “Measurement setup” tab, adjust measurement parameters:
   a. Speed: 1x
   b. Backscan (pre-travel): 20 µm
   c. Length (after backscan): 30 µm
   d. Threshold: 2%
   e. Illumination: use default
   f. Autoscan enabled: 10 µm, 50%



Measurement of roughness – step 4

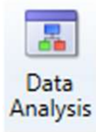
9. Adjust stitching parameters
   a. Enable stitching
   b. Type: rectangular, bounding box:
      - W=0, H=6*(sampling length)+ 1 mm if stitching in Y
      - W=6*(sampling length)+ 1 mm, H=0 if stitching in X
   c. Overlap: 20%, can be adjusted later if stitching fails
   d. Click reference point and traversal → move to the starting point of the measurement
   e. Check no. of rows against Y value of measurement area (consider the overlap). No. of columns should be 1.
   f. Click on "test", check if sample is moving as intended

10. Start the measurement!

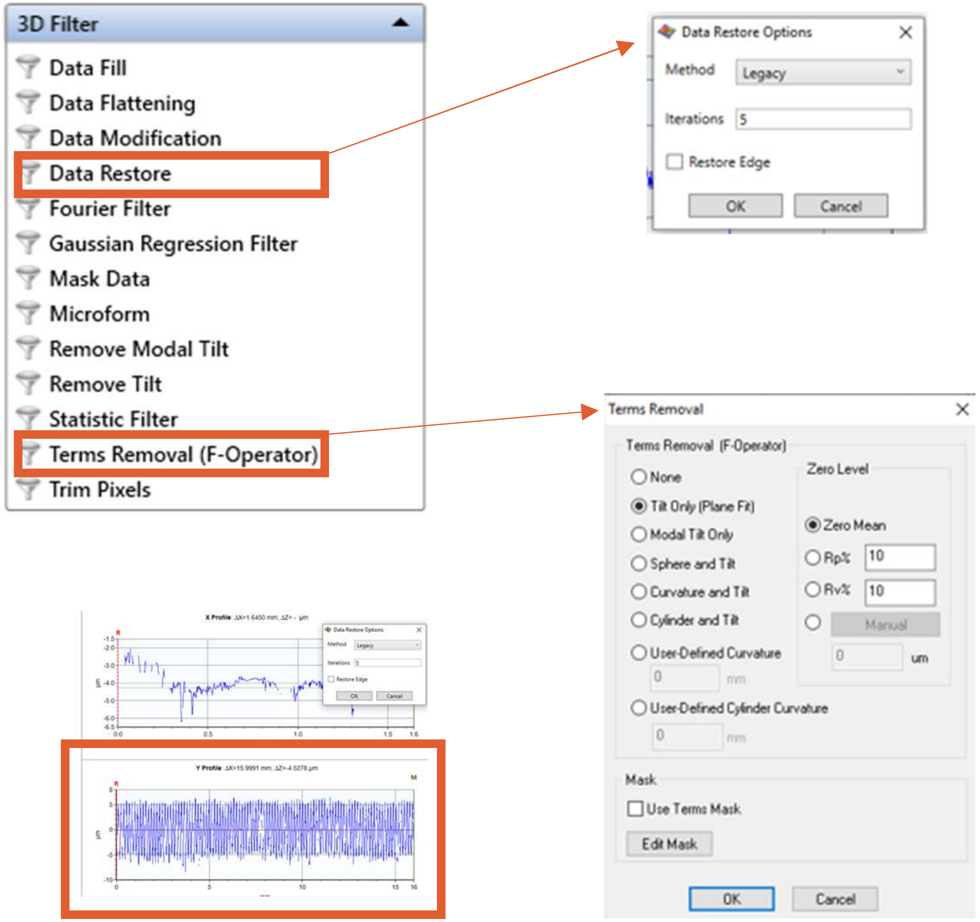


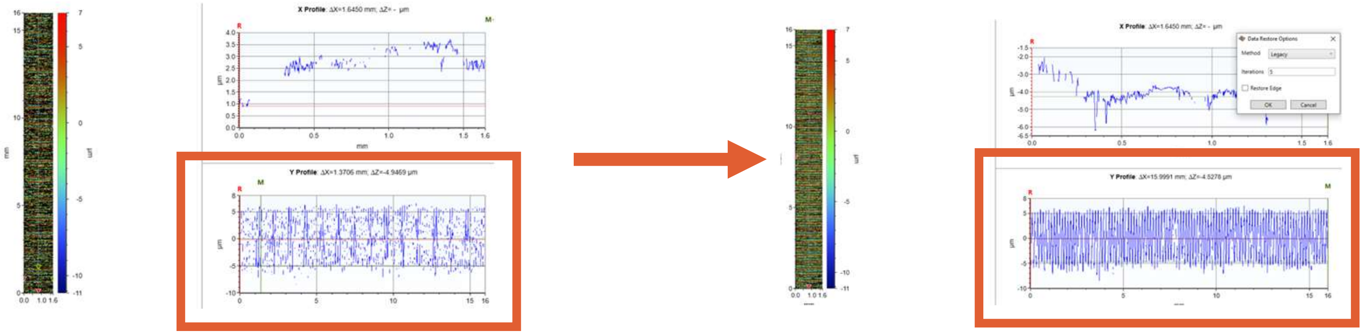
Measurement of roughness – step 5

11. Open “data analysis” section



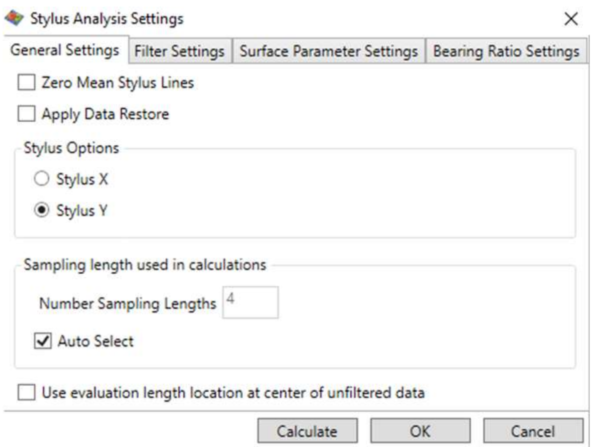
12. Apply F-Operator 3D filter
    - Remove tilt
13. Apply “data restore” filter
    - Start with “legacy” method, 5 iterations. Adjust as necessary

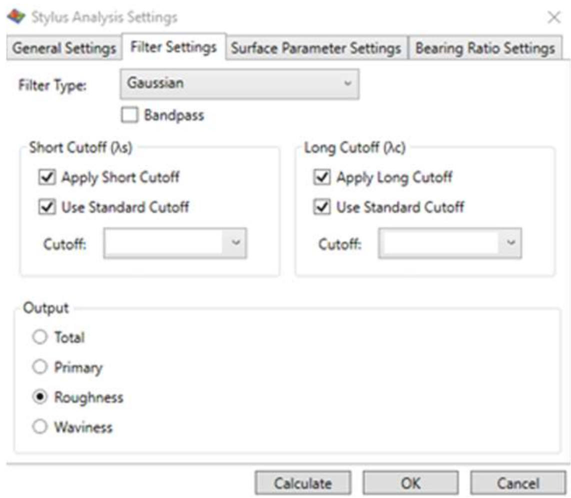


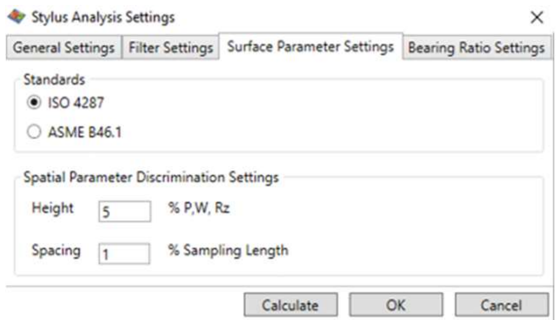


Measurement of roughness – step 5

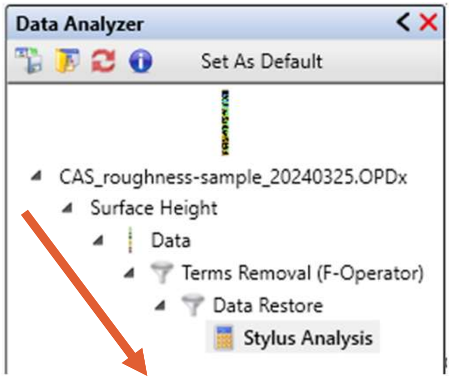
14. Apply "stylus analysis" with appropriate parameters:
    a. Stylus Y
    b. Sampling lengths: auto select
    c. Appropriate cutoffs
    d. Appropriate standard (ISO vs. ASME)





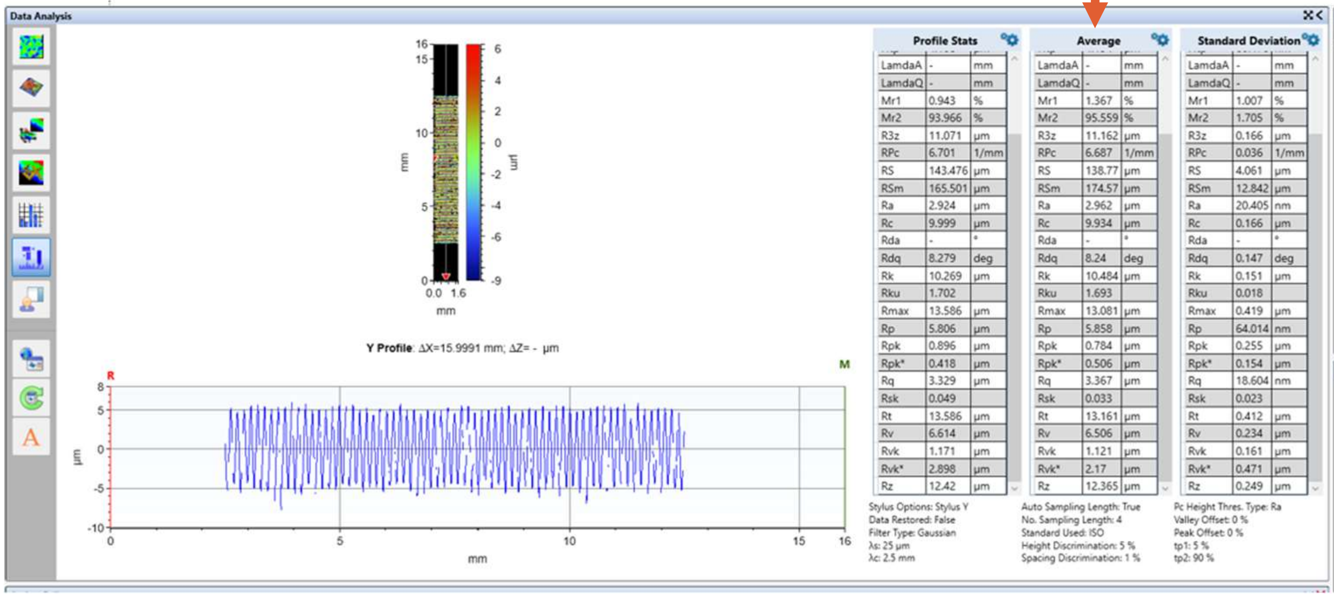


Check that filtering and analysis are applied in the correct sequence



Measurement of roughness – step 6

15. Check results consistency with expected Ra. If not satisfactory, check analysis parameters:
    a. Right cut-offs?
    b. Enough sampling lengths (>=4)?
    c. Right standard?



Measurement of roughness - Troubleshooting

a. If 50% or more data are missing: disable autoscan in step 9, repeat measurement
b. If some “high” data are missing before F-operator is applied: increase backscan in step 9, repeat measurement
c. If some “low” data are missing before F-operator is applied: increase scan length in step 9, repeat measurement
d. If stitching fails: increase overlap in step 9, repeat measurement
e. If data on steep surfaces are missing:
    1. increase data restore iterations
    2. Increase threshold in step 8, repeat measurement

Thank you !

ENGINEERING DEPARTMENT

MECHANICAL & MATERIALS ENGINEERING
FOR PARTICLE ACCELERATORS AND DETECTORS