Introduction to surface roughness and mid-spatial frequency errors

Jessica DeGroote Nelson

Optimax Systems, Inc.

Outline

- What is surface roughness?
- How do we see surface roughness?
- How do we measure surface roughness?
- How do we quantify surface roughness?
- What are mid-spatial frequency errors?

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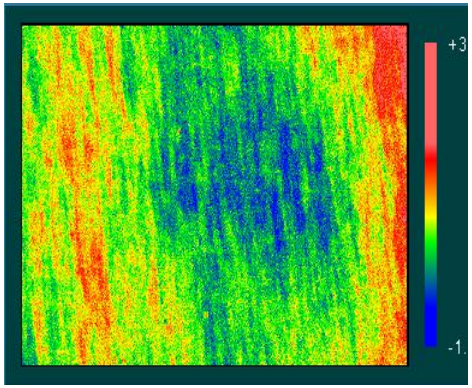
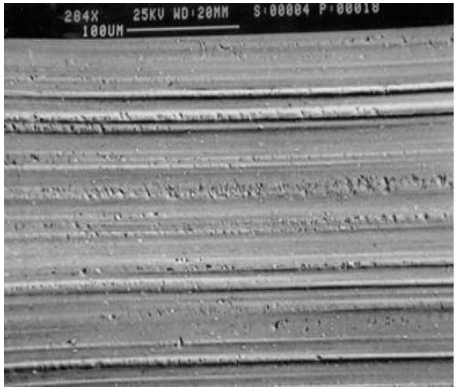
What is surface roughness?

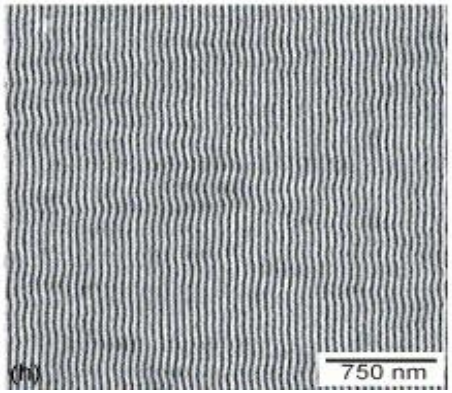
- Roughness is a measure of the topographic relief of a surface
- Examples of surface relief include



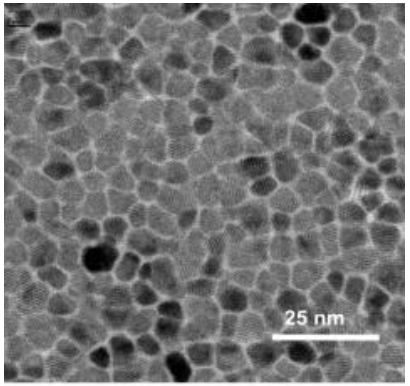
Polishing marks on optical surfaces



Machining marks on machined surfaces



Undulations on silicon wafers



Grains of magnetic material on memory disks

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Schematic representation of a rough surface

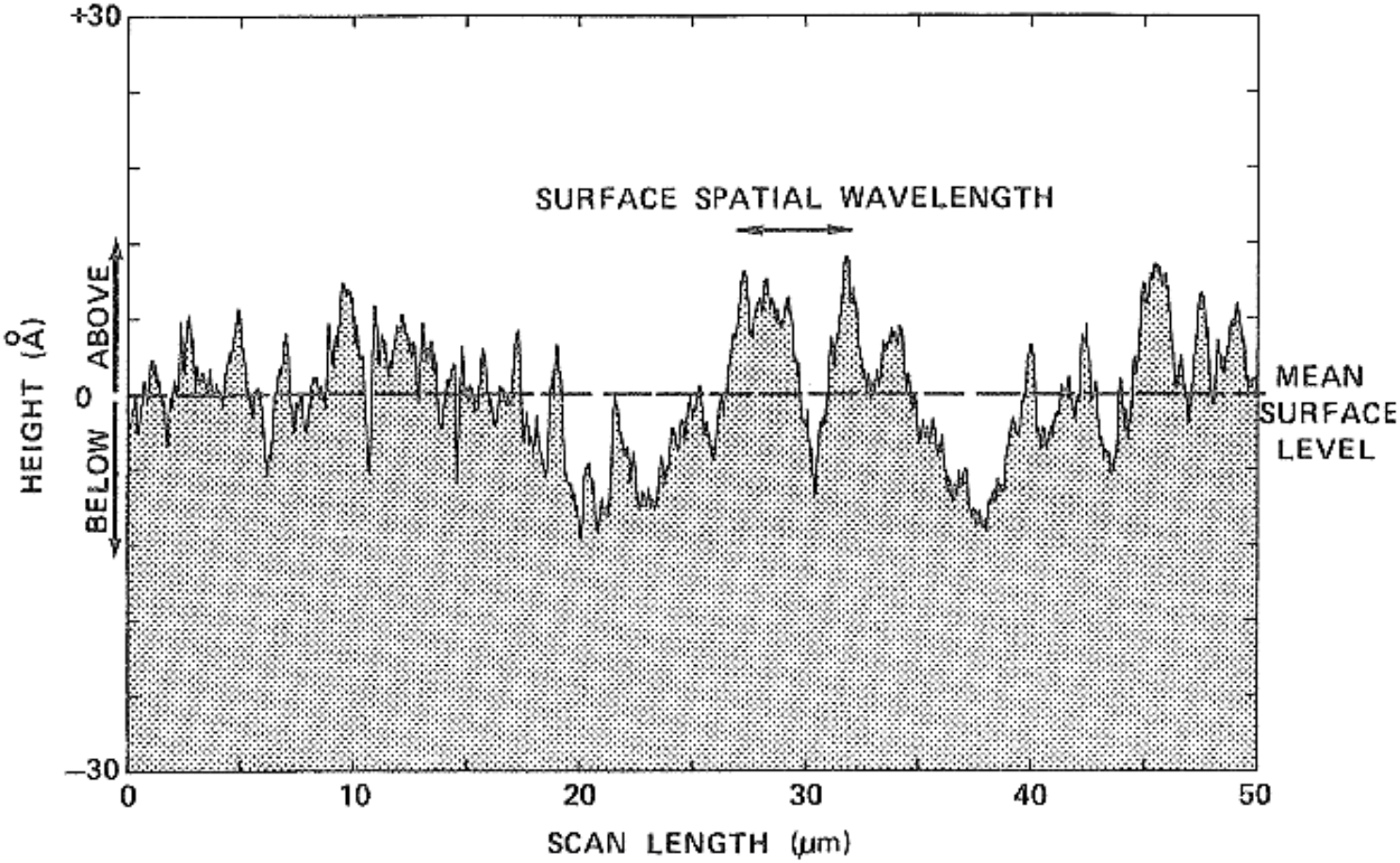

Fig. 1. Schematic representation of a rough surface. The roughness is 4.7 Å rms.

Bennet and Mattsson, "Introduction to Surface Roughness and Scattering" 1999

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How do we see roughness?

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How do we see roughness?

- Unaided eye

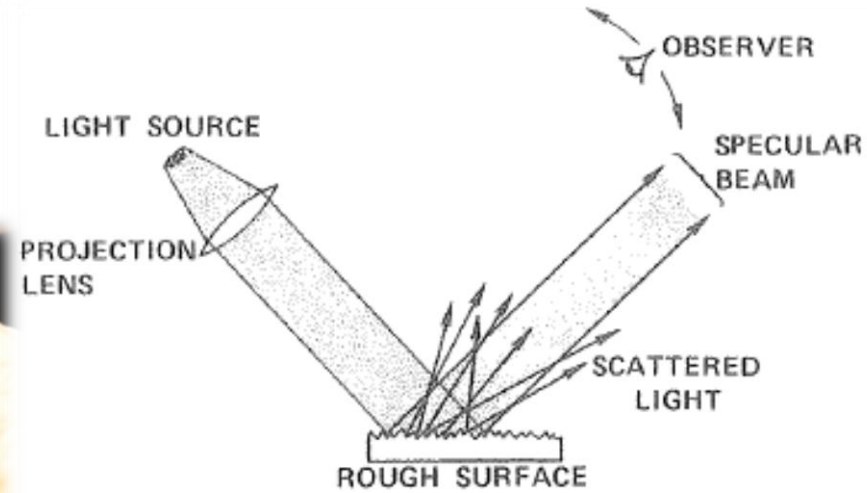

Fig. 2. Diagram for observing scattering from a rough surface.

Bennet and Mattsson, "Introduction to Surface Roughness and Scattering" 1999

Observing light scattered by the surface

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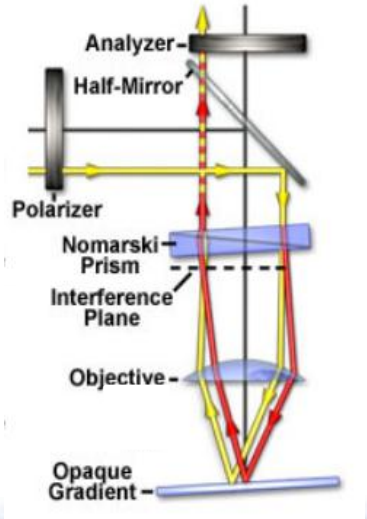
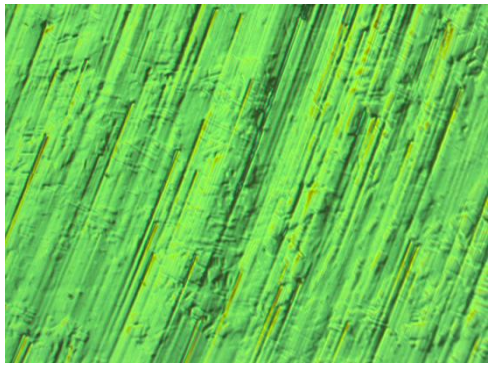
How do we see roughness?

- Unaided eye
- Microscopy
  - Differential Interference Contrast (Nomarski)
  - Electron
  - Scanning Probe
  - Confocal





Nomarski diagram accessed April 21, 2012:
http://www.microscopyu.com/articles/dic/reflecteddic.html

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How do we measure roughness?

- Surface profile measurements
  - Contact methods
  - Non-contact methods
- Scattering measurements

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How do we measure roughness?

- Surface profile measurements
  - Contact methods
    - Stylus (probe) touches the surface
    - Height variations measured as stylus or surface is moved
  - Non-contact methods
- Scattering measurements

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Mechanical Probe Measurements

- With care, the surface measurement accuracy can approach 1 Angstrom (Å)
  - Surface does not need to be reflective
- Problems with mechanical probe measurements:
  - Measure the convolution of the surface with the stylus instead of the surface alone
  - Surface may be scratched during the measurement

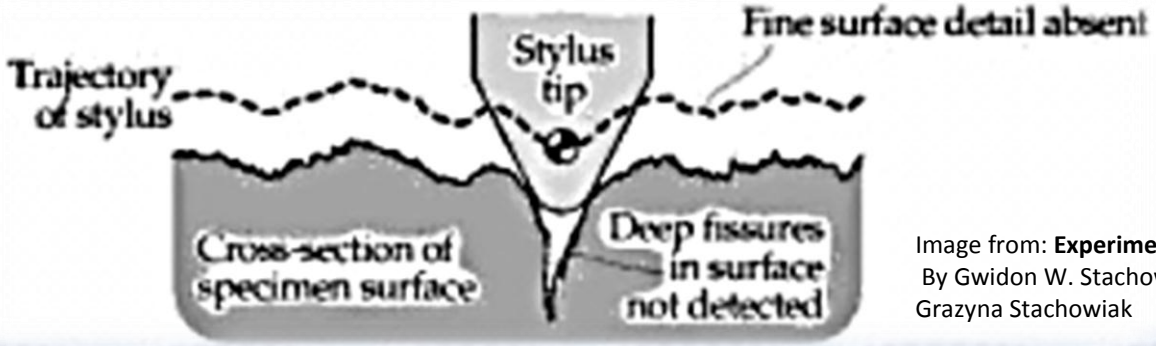

Image from: **Experimental Methods in Tribology**
By Gwidon W. Stachowiak, Andrew W. Batchelor, Grazyna Stachowiak

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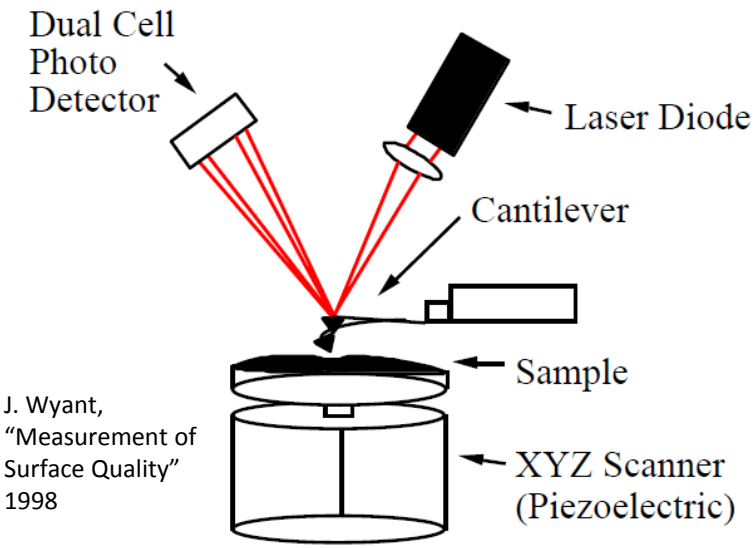
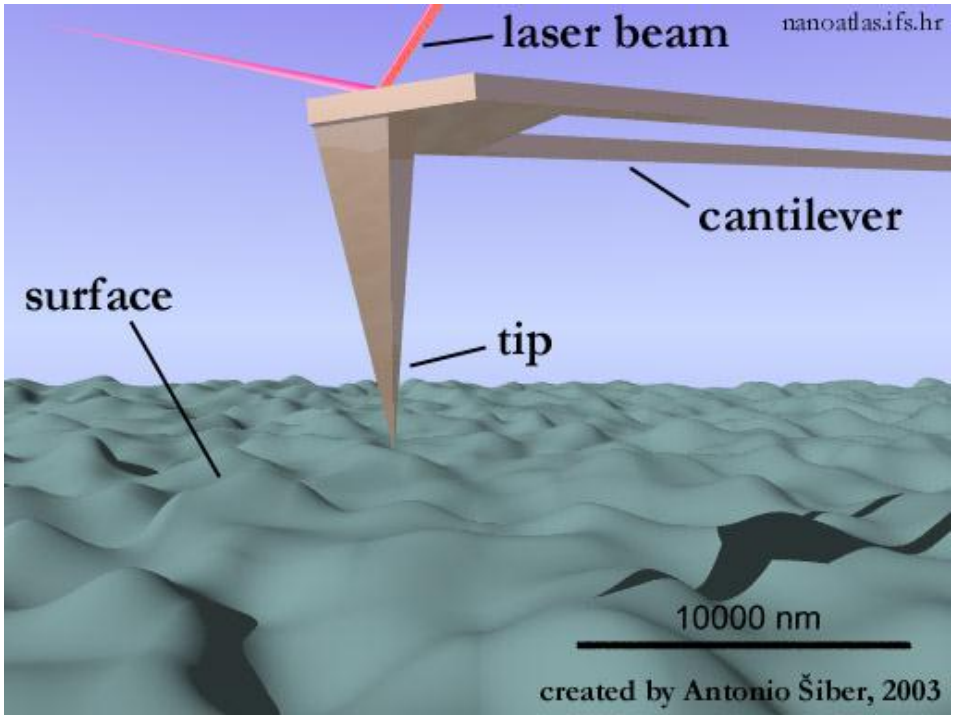
Atomic Force Microscopy (AFM)

- Surface topography of any solid surface



J. Wyant, "Measurement of Surface Quality" 1998



How do we measure roughness?

- Surface profile measurements
  - Contact methods
  - Non-contact methods
    - Optical methods used to examine the surface
- Scattering measurements

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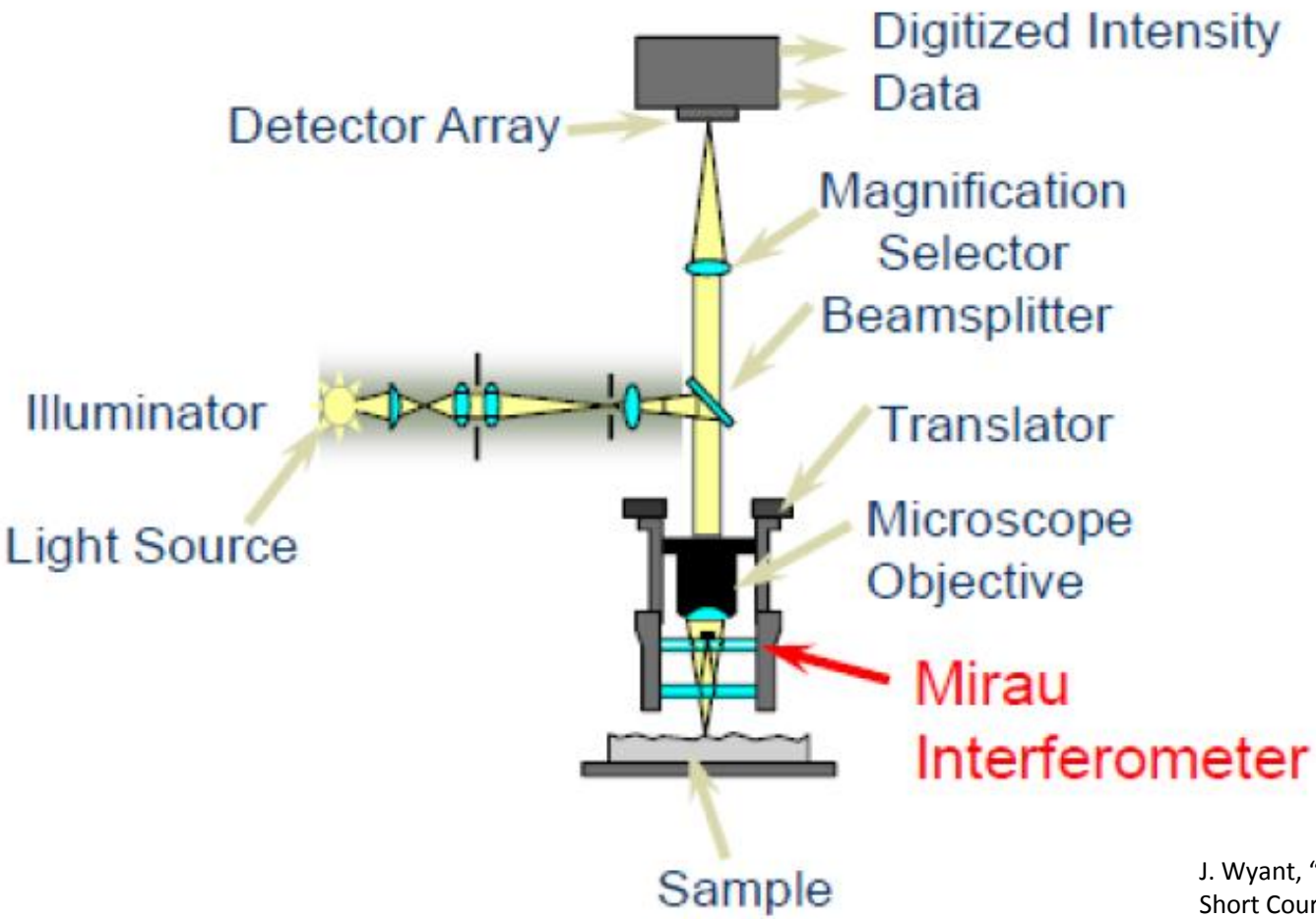
White light interferometer



J. Wyant, "Modern Optical Testing Short Course" 2009

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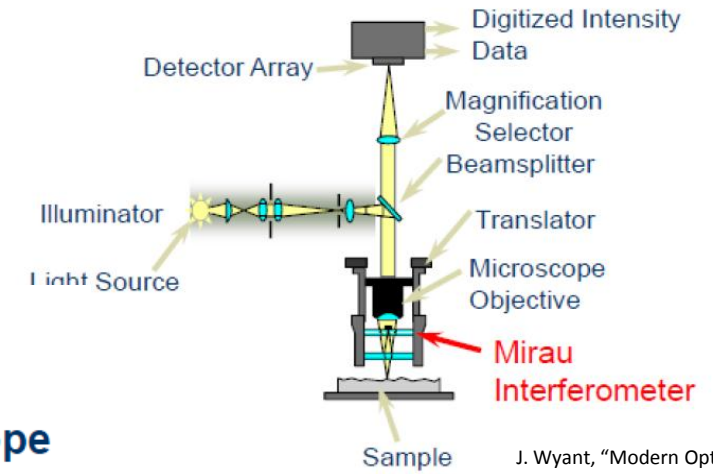
White light interferometer



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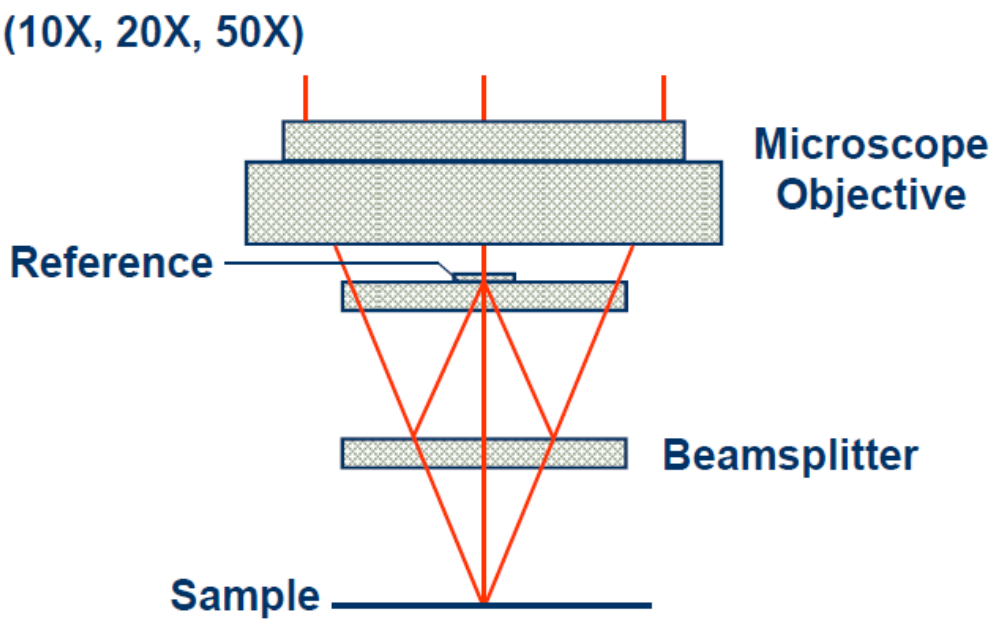
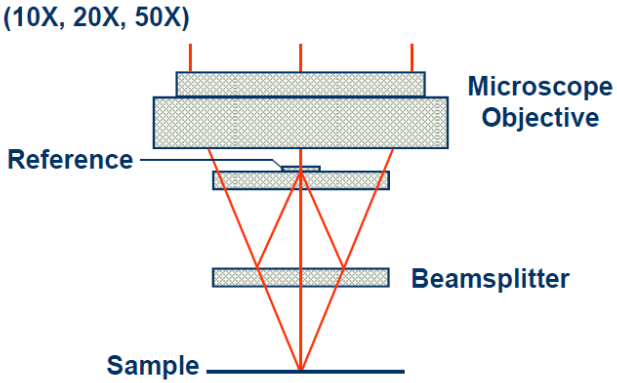
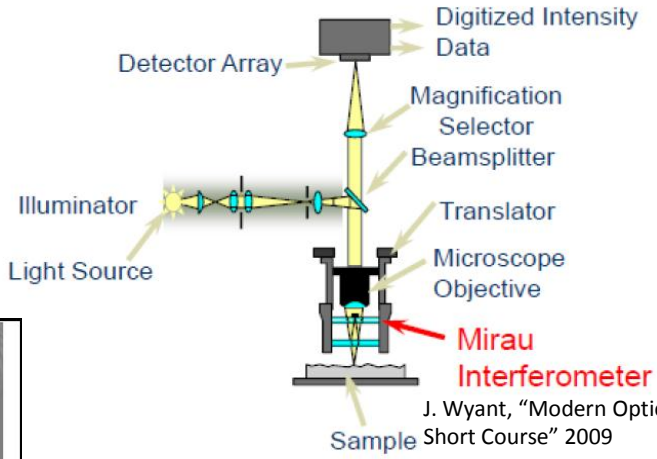


White light interferometer





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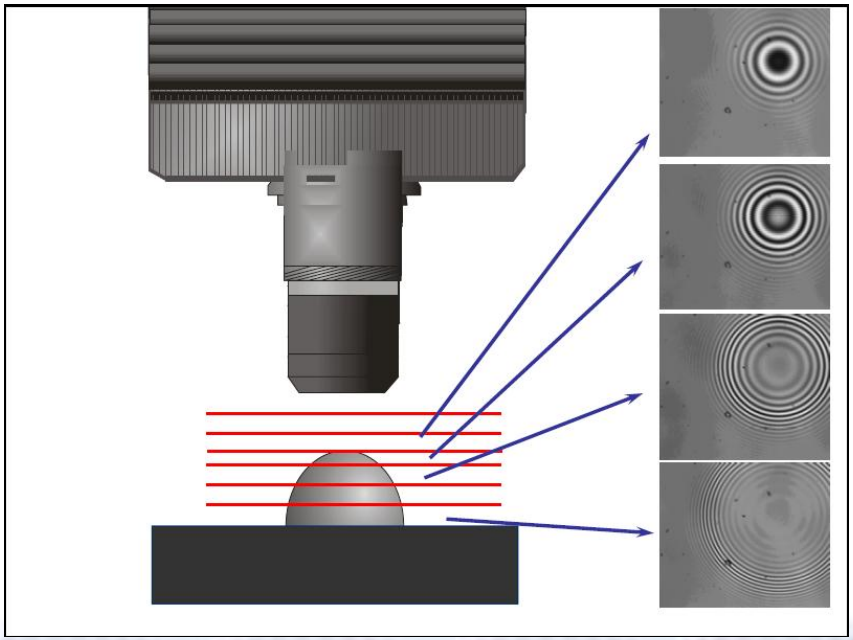

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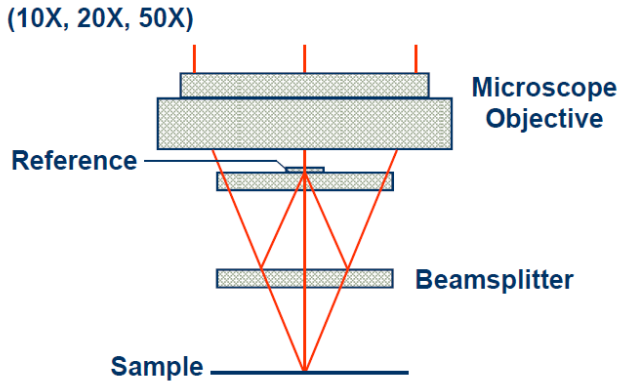
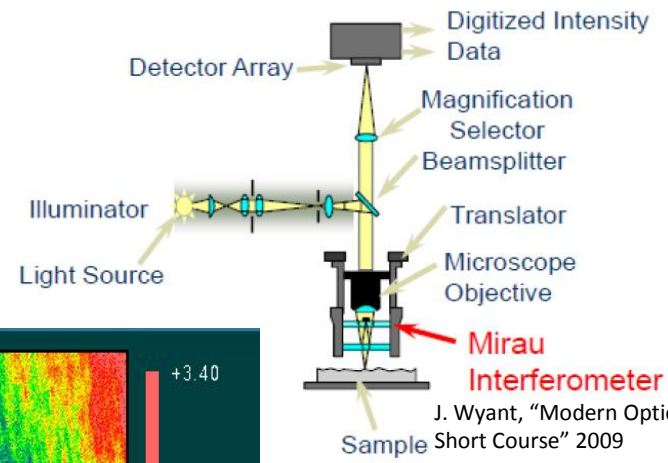
White light interferometer





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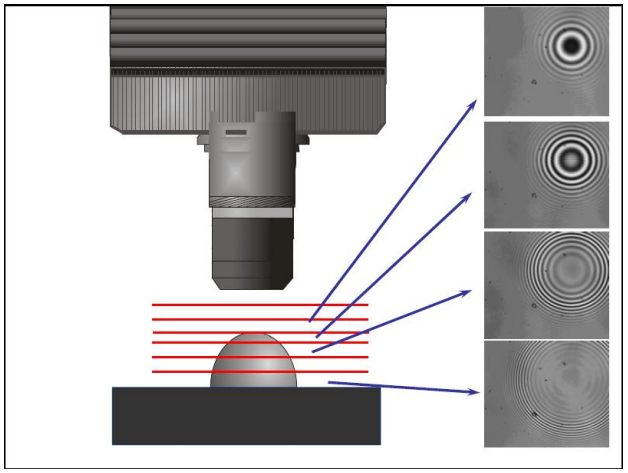

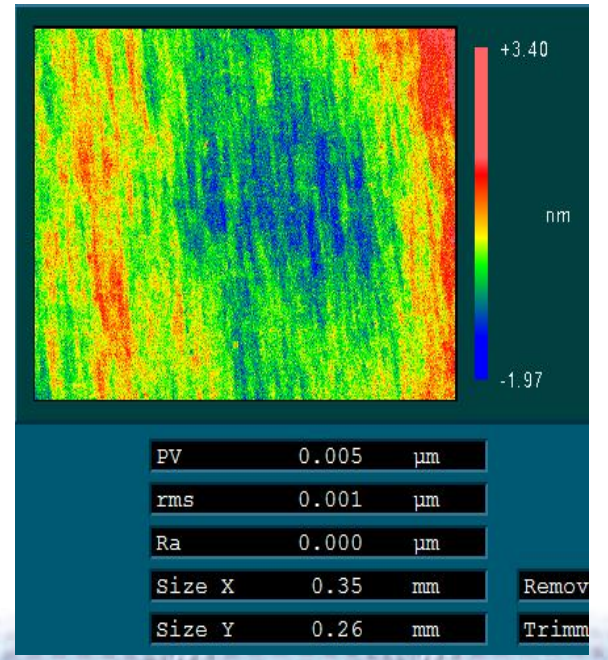

Phase information converted to areal height map indicating x, y and z

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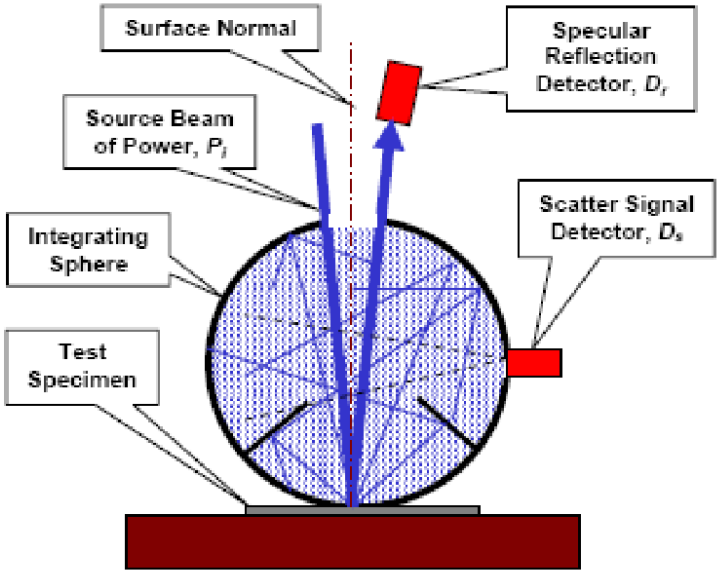
How do we measure roughness?

- Surface profile measuremer
  - Contact methods
  - Non-contact methods
- Scattering measurements
  - Two common measurements
    - Total Integrated Scatter (TIS)
    - Angle-Resolved Scattering (ARS)
  - Scattering caused by particulate contamination will not correlate to roughness



Comparison of methods for determining roughness

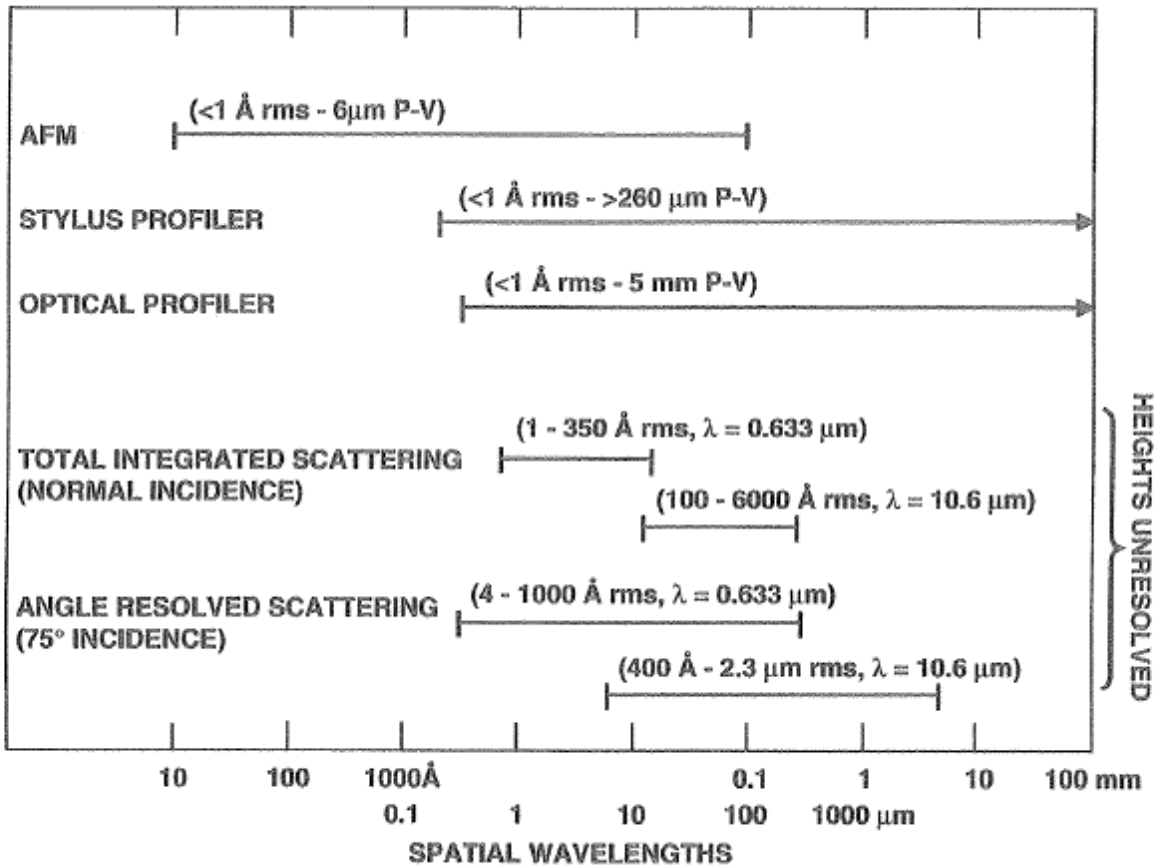


Fig. 22. The horizontal bars give surface spatial wavelength ranges of instruments and techniques for measuring surface roughness. Numbers in parentheses are the range of heights that can be measured with each type of instrument or technique.

Bennet and Mattsson, "Introduction to Surface Roughness and Scattering" 1999

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How do we quantify surface roughness?

- ISO 10110-8:2010 lists five statistical methods for describing optically smooth surfaces
  - rms roughness, Rq
  - rms waviness, Wq
  - Density of microdefects
  - Power spectral density (PSD) function
  - rms slope

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Root Mean Square (RMS or Rq)

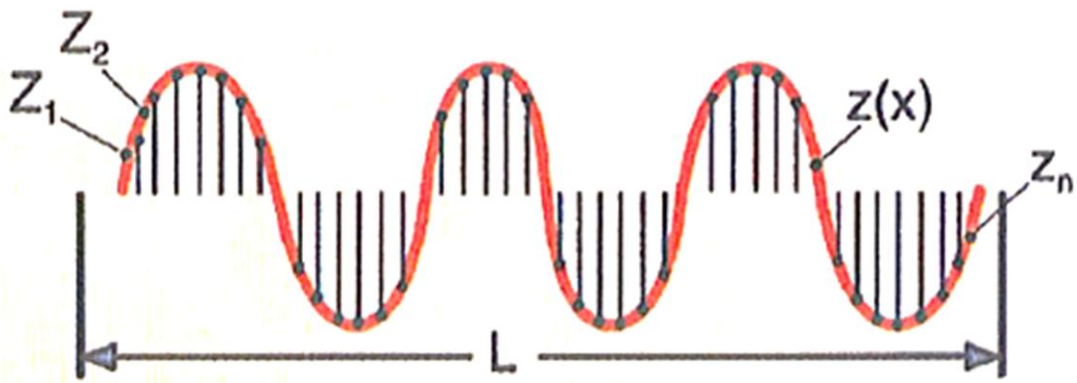

Figure 1 A surface roughness profile $z(x)$ can be approximated by digital means ($z_1 \ldots z_N$).

$$Rq = \left[\frac{1}{L} \int_0^L z^2(x)\, dx \right]^{1/2}$$

$$Rq = \left[\frac{1}{N} \sum_{i=1}^{N} z_i^2 \right]^{1/2}$$

Vorburger, "In the Rough", 2002

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Quantification of microdefects

- Localized pits on an optically smooth surface
- N indicates the permissible number of "markedly" deep pits occur in either a 10mm profile or 300 x 300μm areal region

Polishing grade designation	Number, N, of microdefects per 10 mm of sampling length
P1	$80 \leqslant \quad < 400$
P2	$16 \leqslant N < 80$
P3	$3 \leqslant N < 16$
P4	$N < 3$

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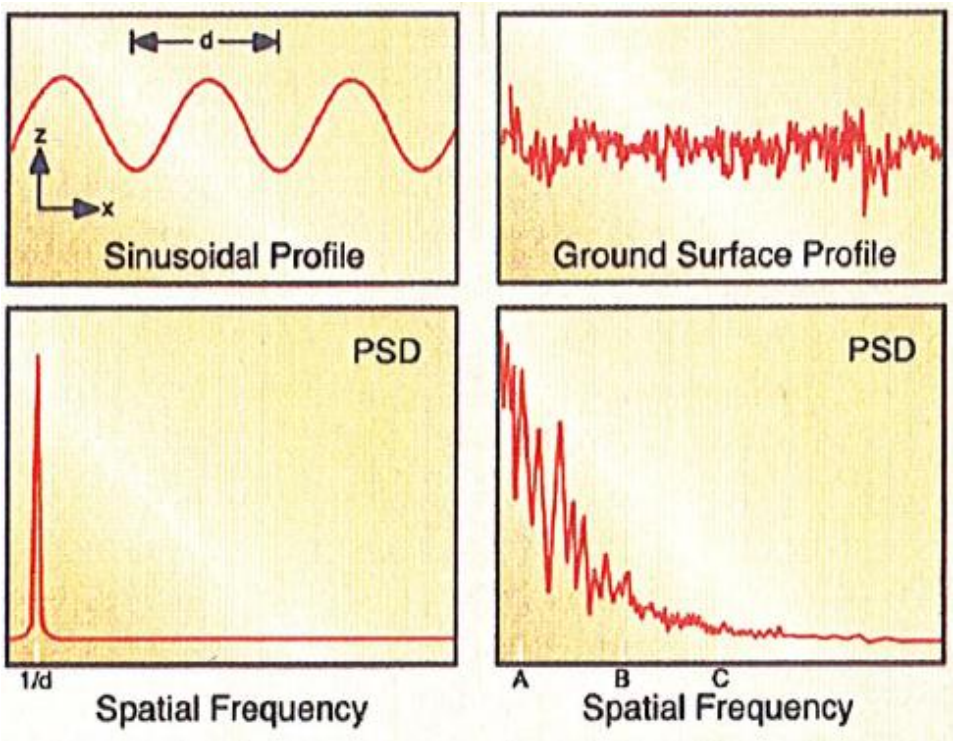
Power Spectral Density (PSD)

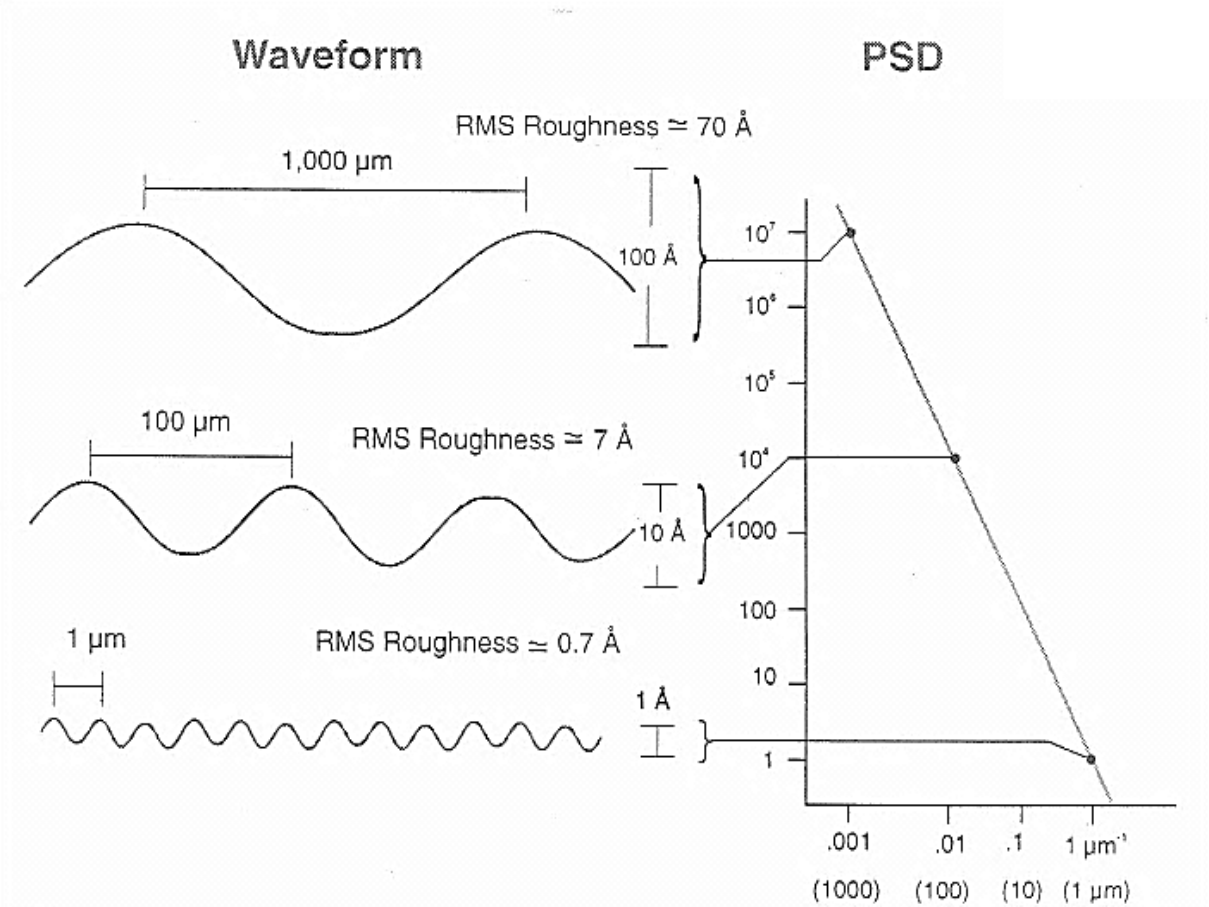
- Squared magnitude of the Fourier transform of the residual surface height along one dimension of the surface profile



$$\mathrm{PSD}(F_j) = \frac{\Delta}{N} \left| \sum_{k=1}^{N} z_k \exp(2\pi i)\, jk / N \right|^2$$

Vorburger, “In the Rough”, 2002

Relationship between PSD and rms surface roughness



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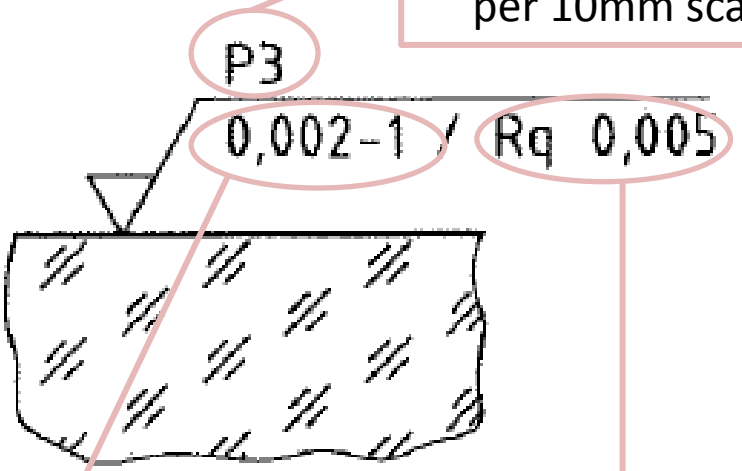
Specifying rms roughness on an optical drawing

ISO method



Polishing grade of <16 microdefects per 10mm scan

Spatial bandwidth 2μm – 1mm

Maximum rms surface roughness: 5nm

Note method

rms roughness specification given as a note on a drawing:

Note: Rq = 5nm over a 2μm – 1mm spatial bandwidth region

- ISO 10110-8:2010 default spatial bandwidth if not given on drawing: 2.5 – 80μm

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Guideline for surface roughness tolerance

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QUICK	RELIABLE	QUALITY

Optimax provides rapid delivery services for a wide variety of optics ranging in size from 10-100mm. Specifications below are general guidelines for tolerancing prototype optics with optical surfaces of f/1 or slower. Tighter tolerances may be possible depending on part specific size, shape and/or material. Optimax stocks a large inventory of ECO-FRIENDLY preferred glasses, see listing.

ASPHERES ▲ CYLINDERS ▲ PRISMS ▲ SPHERES

OPTICS MANUFACTURING TOLERANCES

ATTRIBUTE	COMMERCIAL QUALITY	PRECISION QUALITY	HIGH PRECISION QUALITY
GLASS MATERIAL (n_d, v_d)	±0.001, ±0.8%	±0.0005, ±0.5%	Melt Data
DIAMETER (mm)	+0.00/-0.10	+0.000/-0.025	+0.000/-0.015
CENTER THICKNESS (mm)	±0.150	±0.050	±0.025
SAG (mm)	±0.050	±0.025	±0.015
CLEAR APERTURE	80%	90%	90%
RADIUS	±0.2% or 5 fr	±0.1% or 3 fr	±0.05% or 1 fr
IRREGULARITY - Interferometer (fringes)	2	0.5	0.2
IRREGULARITY - Profilometer (microns)	±10	±1	±0.5
WEDGE LENS (ETD, mm)	0.050	0.010	0.005
WEDGE PRISM (TIA, arc min)	±5	±1	±0.5
BEVELS (face width @ 45°, mm)	<1.0	<0.5	<0.5
SCRATCH - DIG (MIL-PRF-13830B)	80 - 50	60 - 40	20-10
SURFACE ROUGHNESS (Å rms)	50	20	10
AR COATING (R_{Ave})	MgF_2 R < 1.5%	BBAR R < 0.5%	V-coat R < 0.2%

PROTOTYPE OPTICS IN 1 WEEK 0110HP

Commercial Quality: 5nm rms

Precision Quality: 2nm rms

High Precision Quality: 1nm rms

Default bandwidth 2.5 – 80μm

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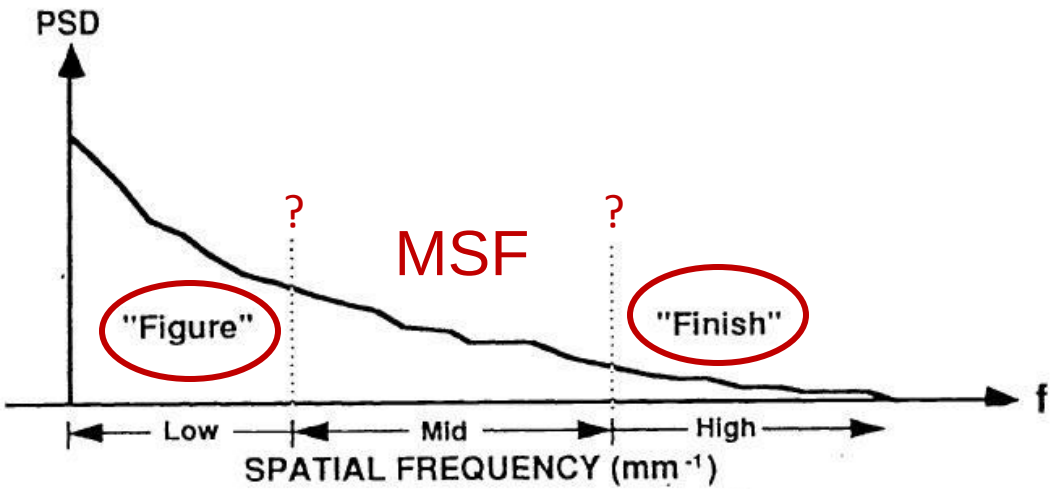
What is “mid-spatial frequency”?



J.E. Harvey and A. Kotha, “Scattering effects from residual optical fabrication errors, Proc. SPIE 2576-25

D. Aikens, J. E. DeGroote, and R. N. Youngworth, "Specification and Control of Mid-Spatial Frequency Wavefront Errors in Optical Systems," (Optical Society of America, 2008).

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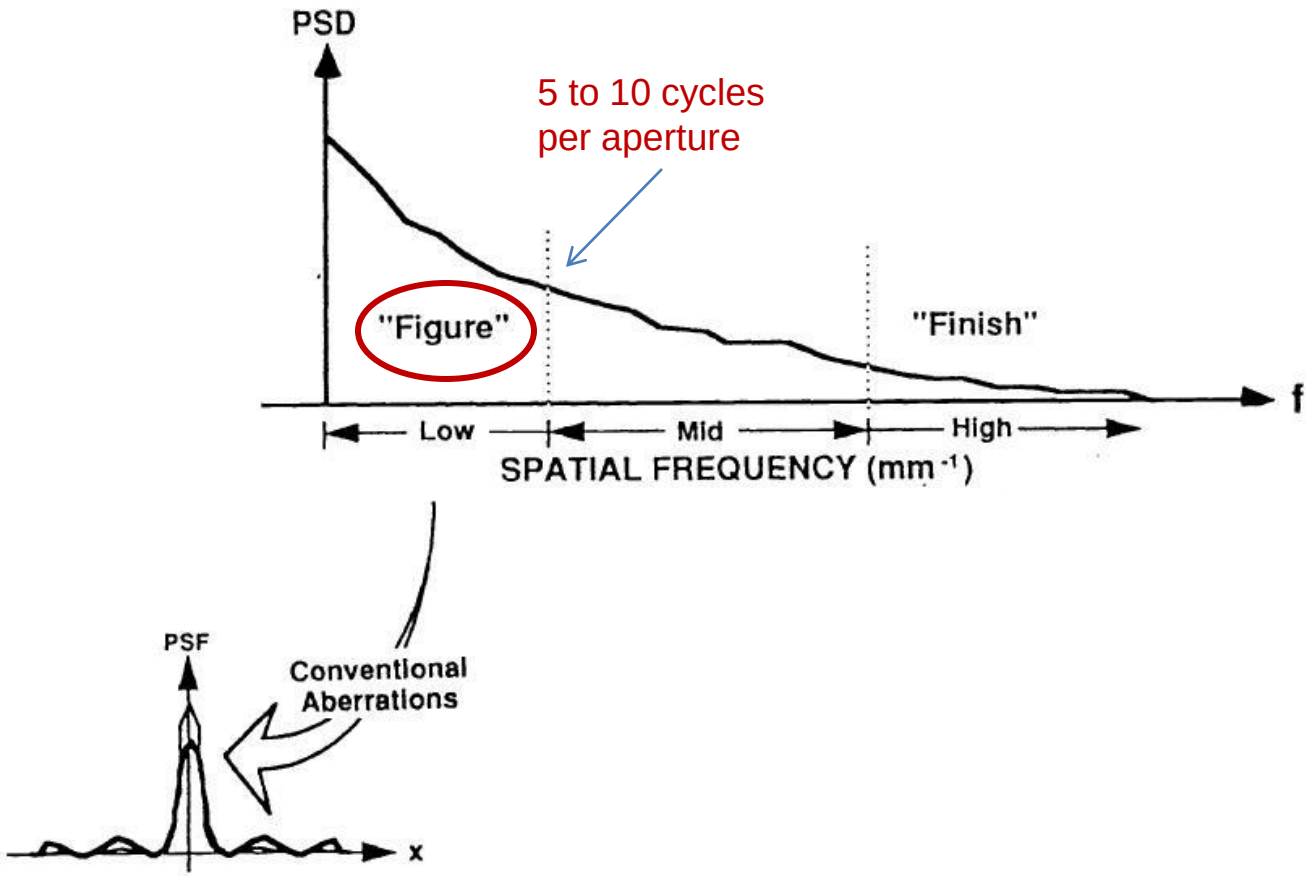
Figure is the range of spatial frequencies addressable with a simple Zernike expansion



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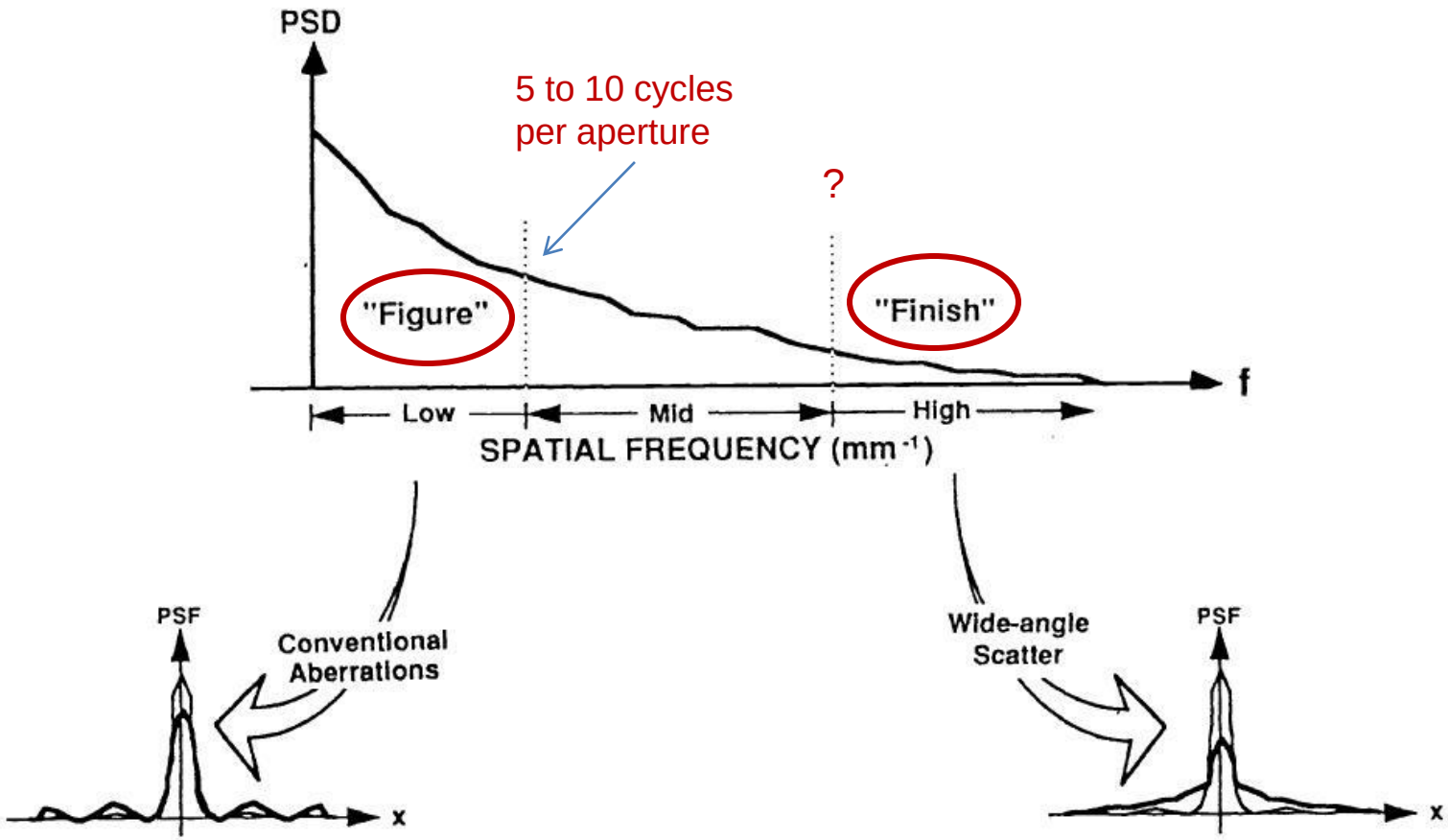
Finish (a.k.a “gloss” or “roughness”) is results in total transmission loss due to scatter



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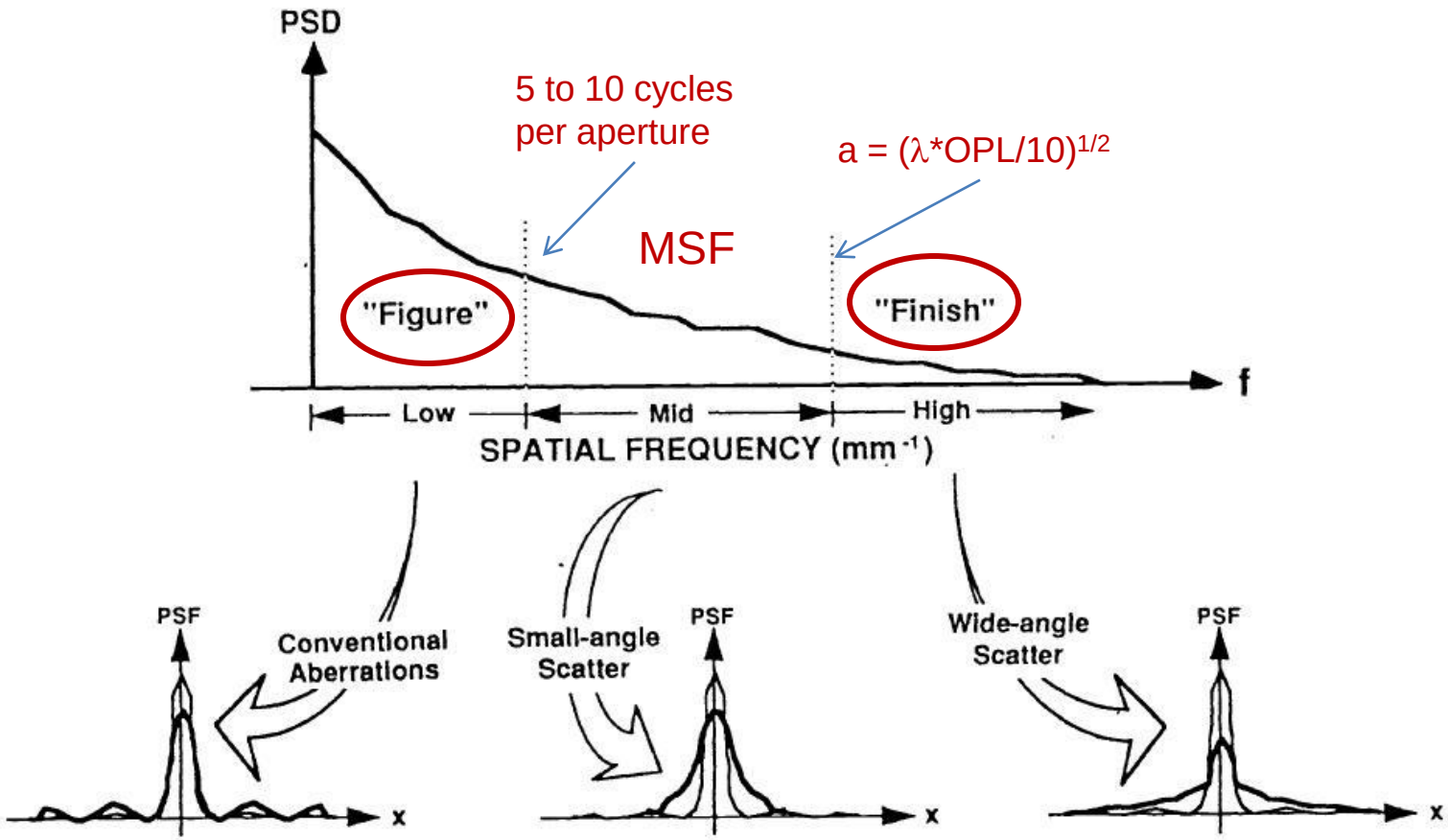
Mid-Spatial Frequency bandwith limits help to define the MSF itself



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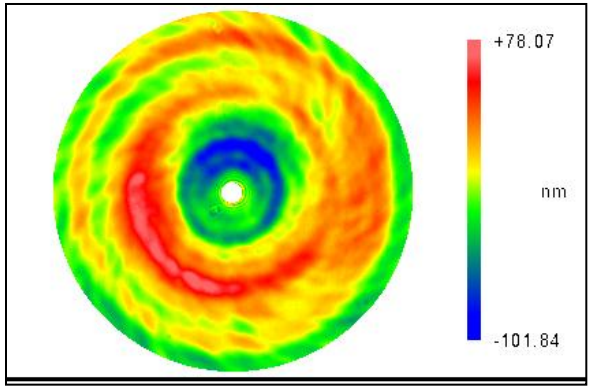
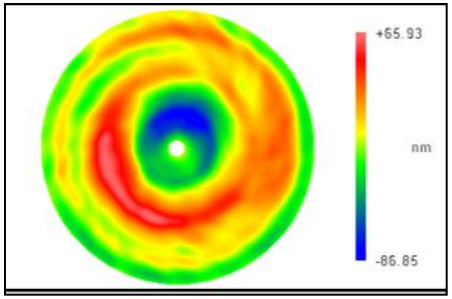
Example: Spoke and Spiral Errors

PV: 179.9nm
RMS: 28.6nm



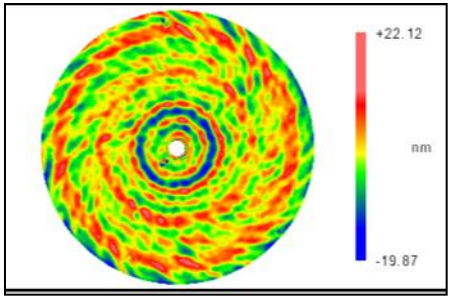
Unfiltered data

PV: 152.8nm
RMS: 26.3nm



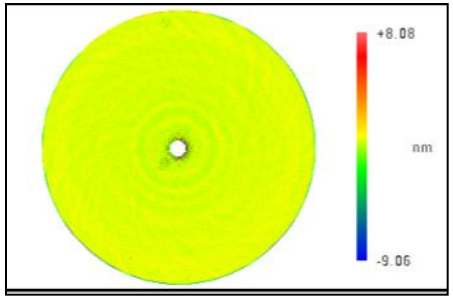
Low spatial frequency

PV: 41.9nm
RMS: 4.8nm



Mid-spatial frequency

PV: 17.1nm
RMS: 0.6nm



High spatial frequency

D. Aikens, J. E. DeGroote, and R. N. Youngworth, "Specification and Control of Mid-Spatial Frequency Wavefront Errors in Optical Systems," (Optical Society of America, 2008).

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Characterizing MSF Errors

- Band Limited RMS and Power Spectral Density
- Slope Error
- Zernike Residual RMS

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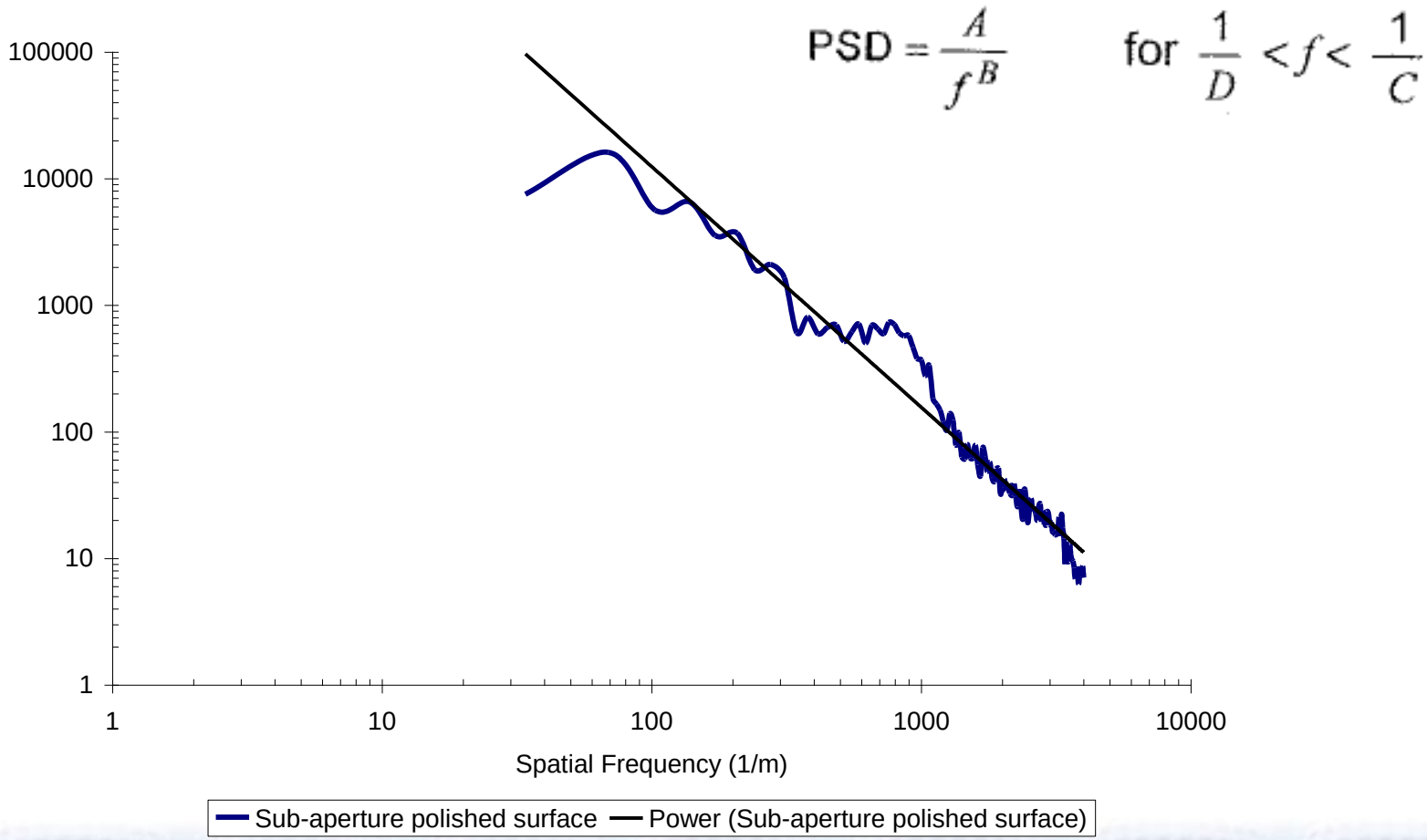
Power Spectral Density (PSD)

- Deviation from straight line



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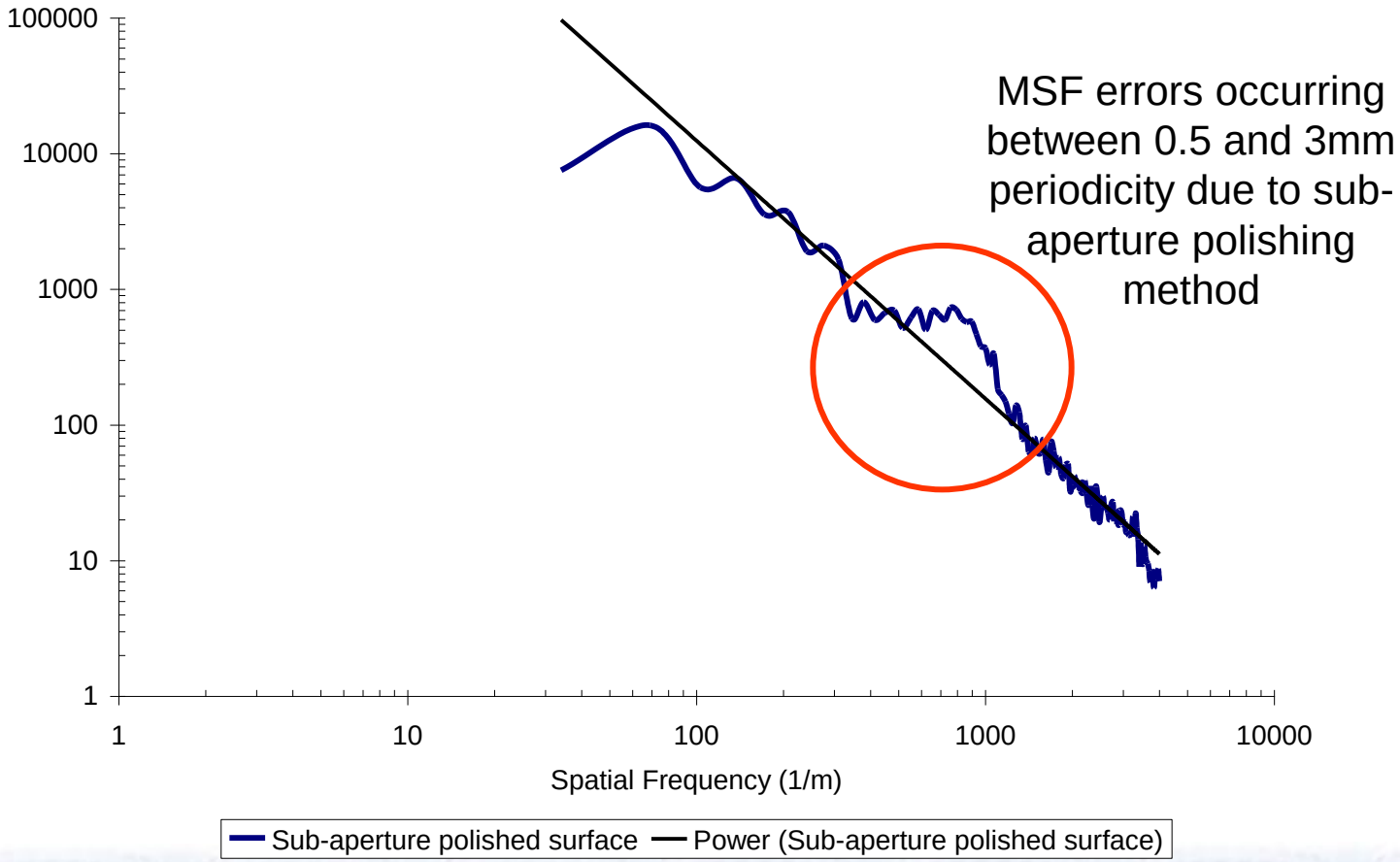
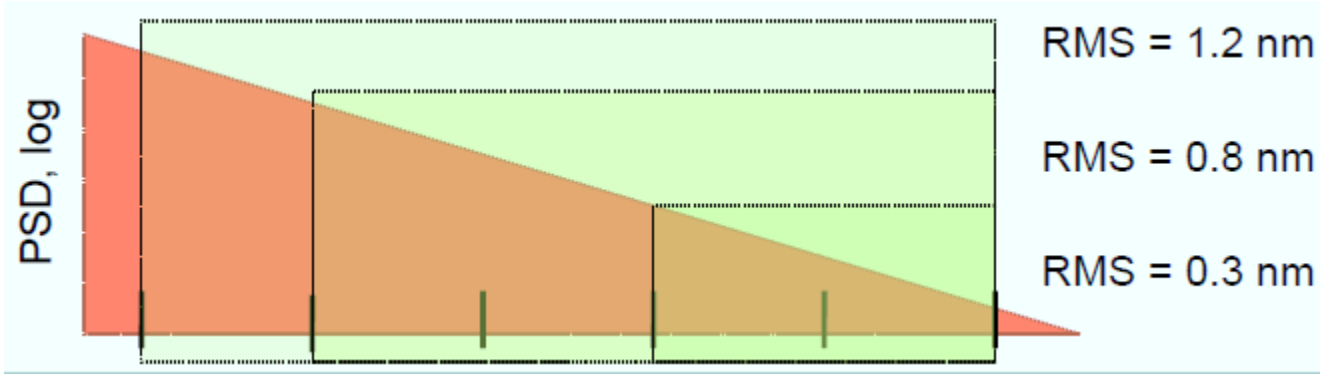
Power Spectral Density (PSD)

- Deviation from straight line



Band-limited RMS and PSD

- *RMS is proportional to square root of area of PSD*
  - *RMS is a function of the spatial frequency limits*
- An RMS roughness specification without a spatial frequency limit is MEANINGLESS!



Spatial Frequency, log

- Also important to consider how the surface will be measured

Slope Specification

- Slope is the difference between the heights at two points on the surface divided by the distance between the two points
  - Expressed in angular units
- Complete slope specification contains
  - Slope specification (angular units)
    - Specify Peak or RMS
      - Default: RMS
  - Integration length
    - Default: 4% CA
  - Spatial bandwidth

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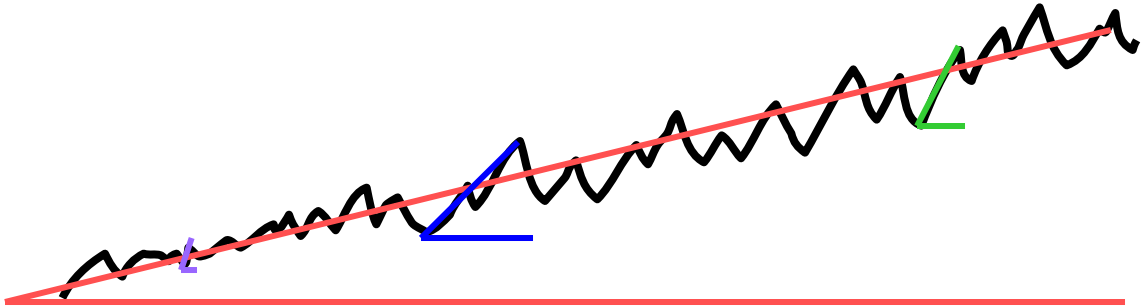
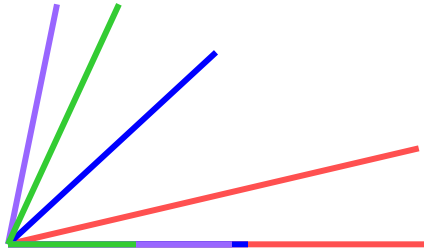
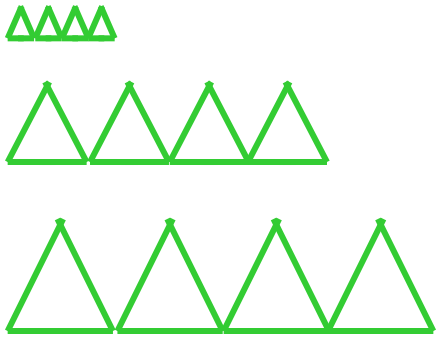
Integration length corresponds to the unwanted "feature size"







1 – 2mm integration lengths are recommended when trying to pinpoint sub-aperture polishing tool marks

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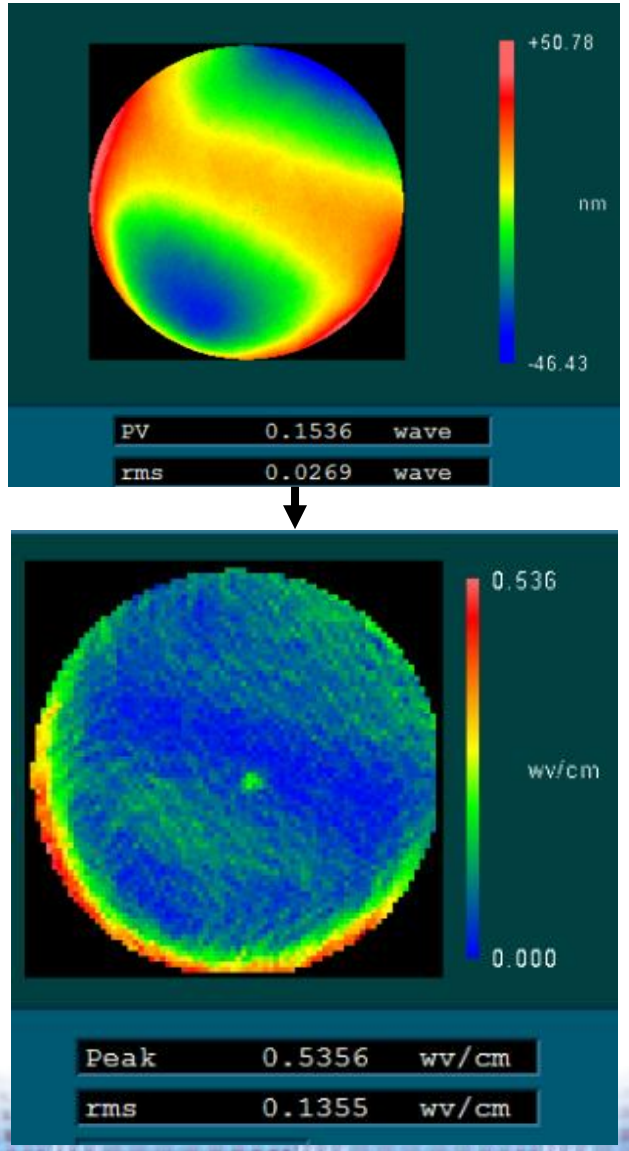
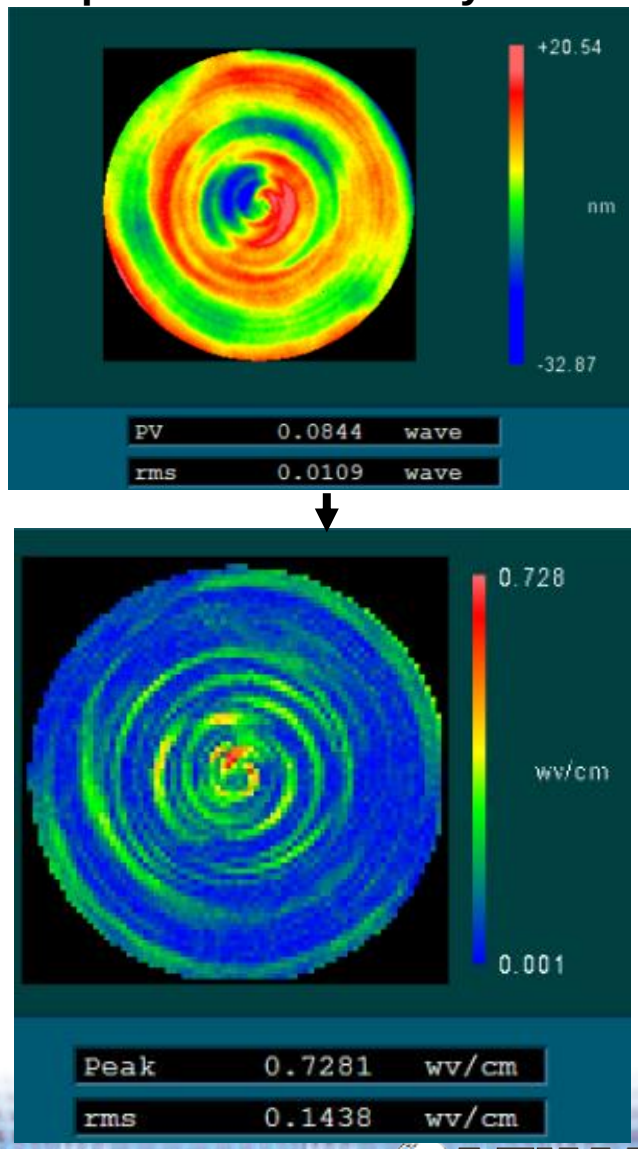
Slope data

Pitch Polished



Sub-aperture Rotationally Polished



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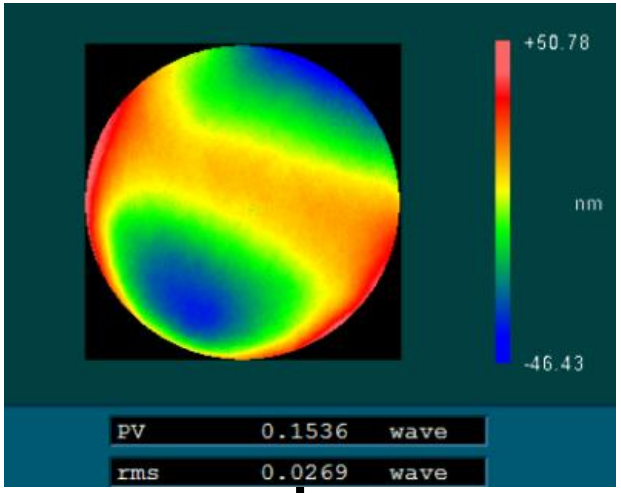
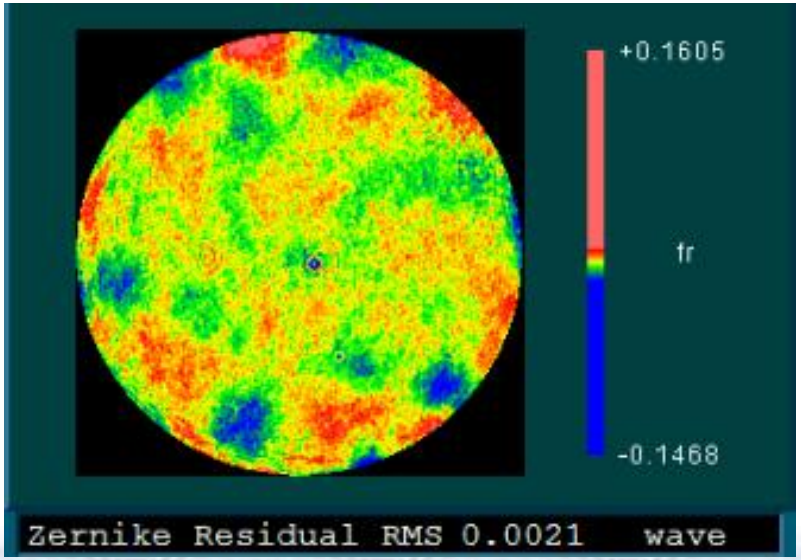
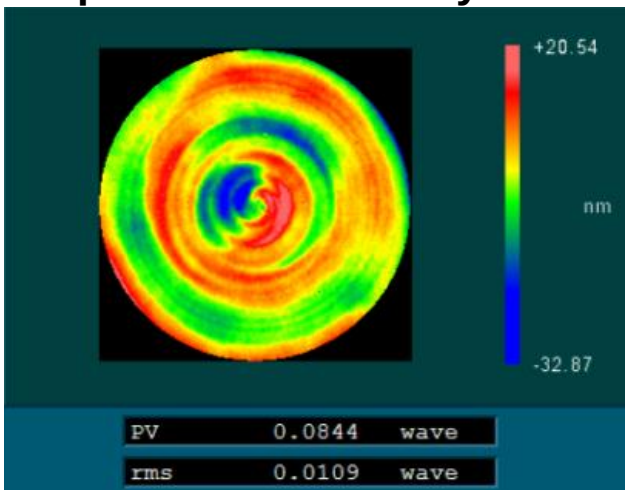
Zernike Residual RMS (after 37 term Zernike removed)

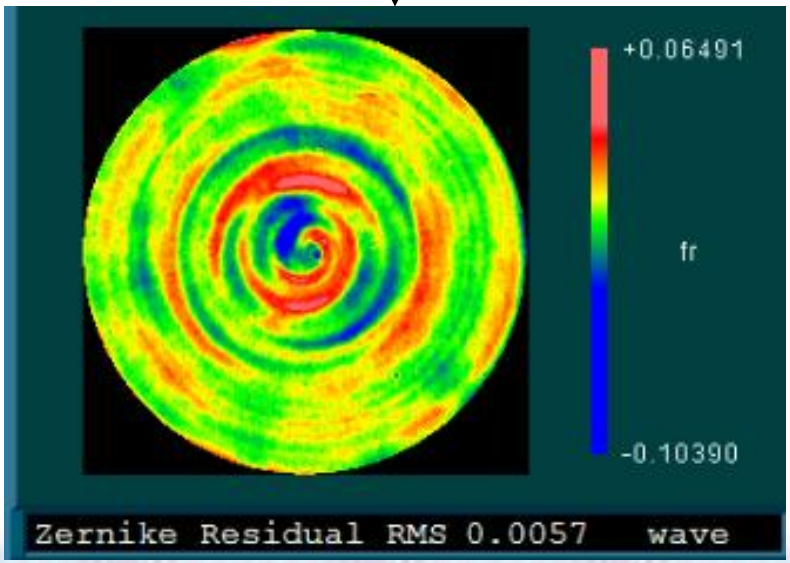
Pitch Polished





Sub-aperture Rotationally Polished





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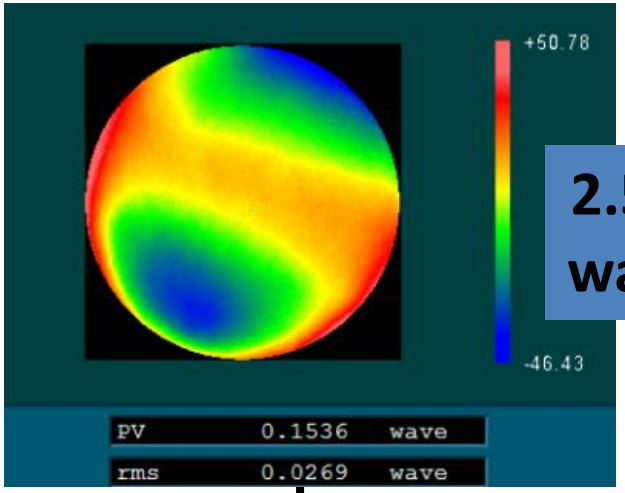
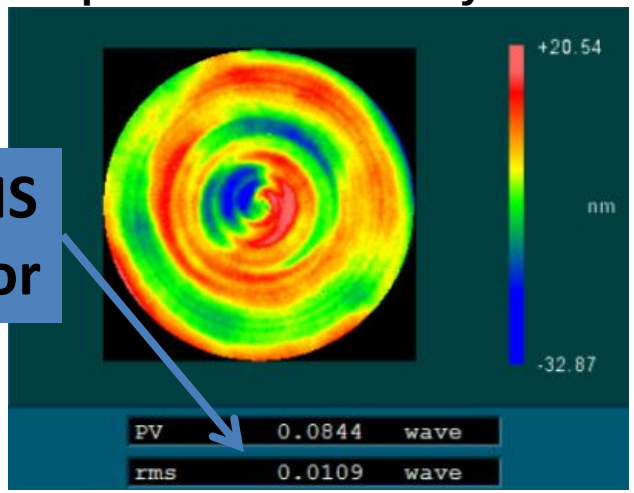
Zernike Residual RMS

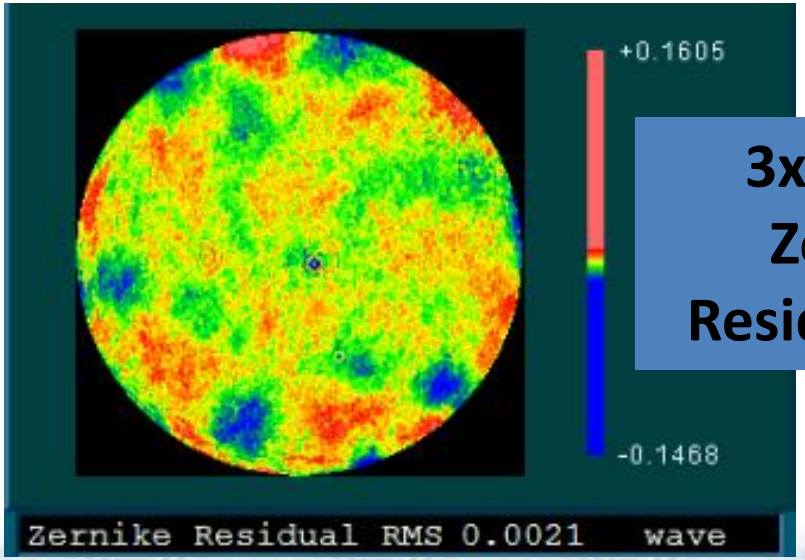
Pitch Polished

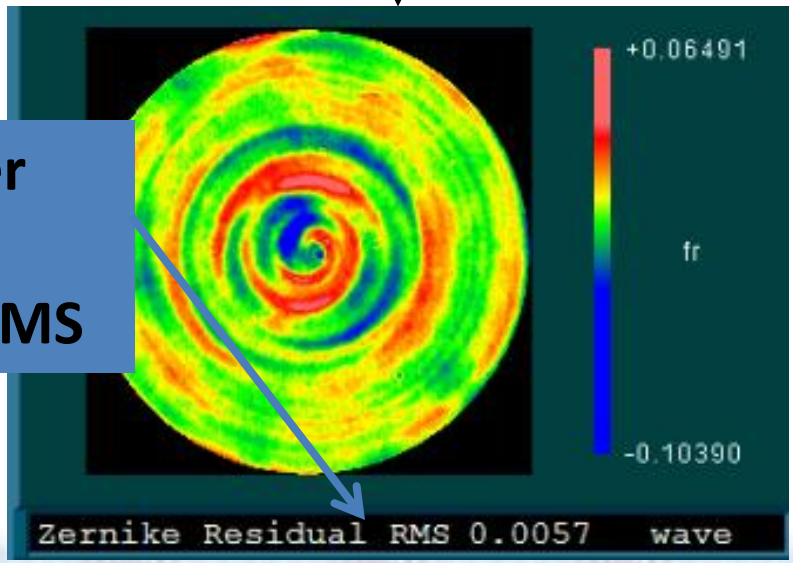


Sub-aperture Rotationally Polished



2.5x lower RMS wavefront error





3x higher Zernike Residual RMS

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Conclusion

- What is surface roughness?
- How do we see surface roughness?
- How do we measure surface roughness?
- How do we quantify surface roughness?
- What are mid-spatial frequency errors?

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Conclusion

- What is surface roughness?
  - Roughness is a measure of the topographic relief of a surface
- How do we see surface roughness?
- How do we measure surface roughness?
- How do we quantify surface roughness?
- What are mid-spatial frequency errors?

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Conclusion

- What is surface roughness?
- How do we see surface roughness?
  - Unaided eye and microscopic techniques
- How do we measure surface roughness?
- How do we quantify surface roughness?
- What are mid-spatial frequency errors?

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Conclusion

- What is surface roughness?
- How do we see surface roughness?
- How do we measure surface roughness?
  - Contact and non-contact profilers and scattering techniques
- How do we quantify surface roughness?
- What are mid-spatial frequency errors?

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Conclusion

- What is surface roughness?
- How do we see surface roughness?
- How do we measure surface roughness?
- How do we quantify surface roughness?
  - Recommended: rms value with spatial bandwidth
- What are mid-spatial frequency errors?

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Conclusion

- What is surface roughness?
- How do we see surface roughness?
- How do we measure surface roughness?
- How do we quantify surface roughness?
- What are mid-spatial frequency errors?
  - Region between figure and finish typically causing small angle scatter in a system
    - Worst offender: small tool polishing
  - Recommend quantifying with band-limited rms and slope

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References:

[1] J.M. Bennett, L. Mattson, Introduction to Surface Roughness and Scattering, Optical Society of America, 1999.

[2] D.M. Aikens, J.E. DeGroote, R.N. Youngworth, Specification and Control of Mid-Spatial Frequency Wavefront Errors in Optical Systems, in: Optical Fabrication and Testing, OSA, Rochester, NY, 2008, pp. OTuA1.

[3] R.N. Youngworth, B.D. Stone, Simple estimates for the effects of mid-spatial-frequency surface errors on image quality, Applied Optics, 39 (2000) 2198-2209.

[4] J.E. Harvey, K.L. Lewotsky, A. Kotha, Effects of surface scatter on the optical performance of x-ray synchrotron beam-line mirrors, Applied Optics, 34 (1995) 3024-3032.

[5] ISO, 10110 Part 8, in: Surface texture; roughness and waviness, 2010.

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