Specification and Control of Mid-Spatial Frequency Wavefront Errors in Optical Systems

RICHARD YOUNGWORTH
LIGHT CAPTURE, INC.

JESSICA DEGROOTE
OPTIMAX SYSTEMS, INC.

AND DAVE AIKENS
SAVVY OPTICS CORP.

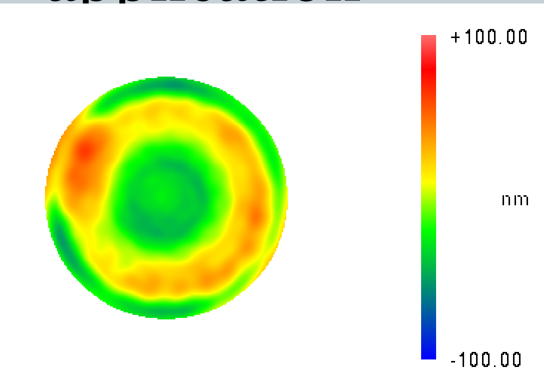
OPTICAL FABRICATION AND TEST
DATE

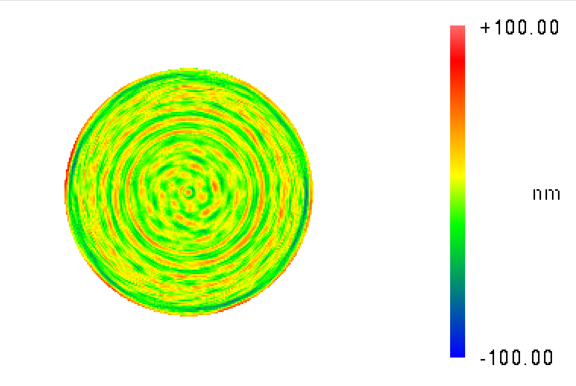
Outline

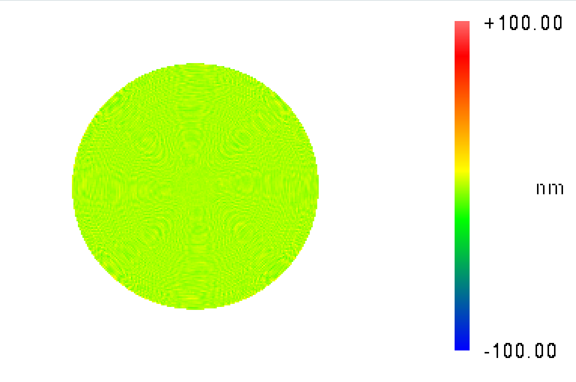
- Surface ripple
  - Definition and examples
  - How it is formed
  - How it is reduced or eliminated
- Mid-spatial frequencies
  - Surface form errors and frequencies
  - Surface roughness errors and frequencies
  - Calculating the limits of the mid-spatial domain
- Specification of mid-spatial frequency ripple
  - Effects on performance
  - Allowable amplitudes
  - Drawing notations
- Summary

Surface Ripple Overview

- Surface ripple is defined as residual, periodic undulations in the surface profile
- Modern sub-aperture and deterministic optical fabrication techniques are more prone to ripple errors
- The spatial frequencies of interest vary according to the application



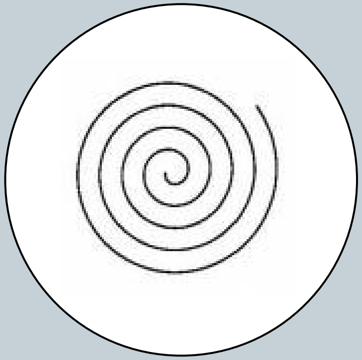




This surface was prepared with a deterministic polishing method and analyzed for three different spatial frequency regions (arbitrarily defined by the authors to highlight tool path errors)

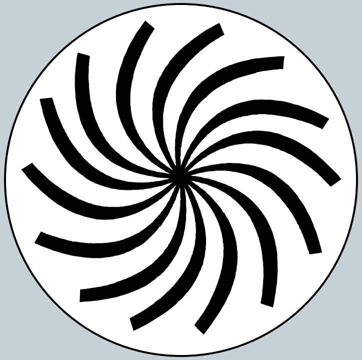
Surface Ripple Formed By Sub-Aperture Deterministic Polishing Methods

- Rotationally Symmetric



Spiral:

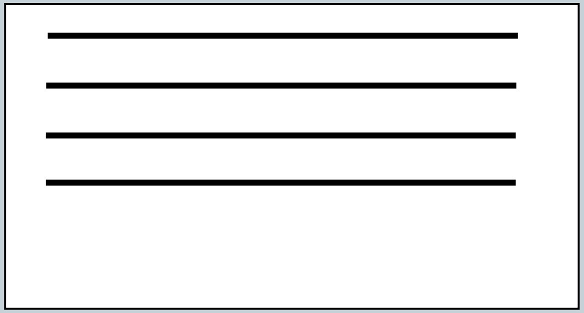
Rotational sub-aperture tool path



Spoke:

Ring tool grinding marks

- Raster Polish

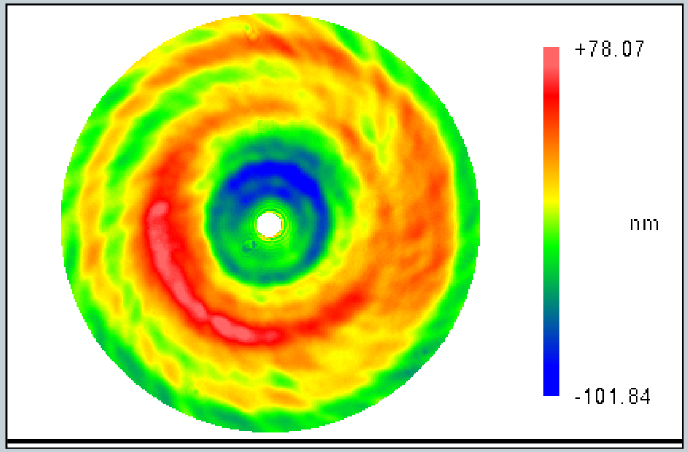


Raster:

Unidirectional scanning sub-aperture tool path

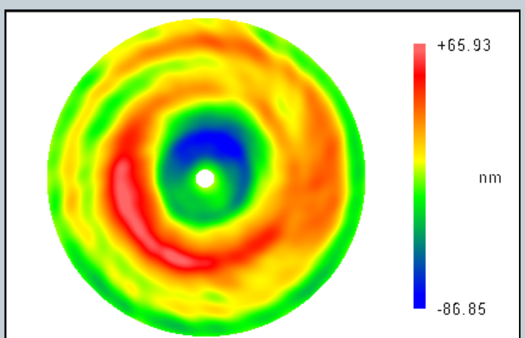
Example: Spoke and Spiral Errors

PV: 179.9nm
RMS: 28.6nm



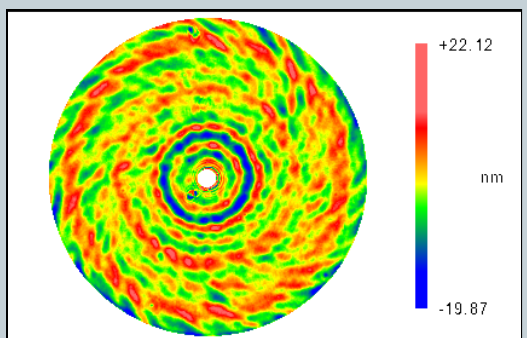
Unfiltered data

PV: 152.8nm
RMS: 26.3nm



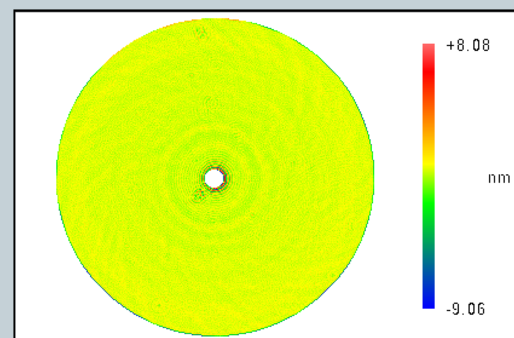
Low spatial frequency

PV: 41.9nm
RMS: 4.8nm



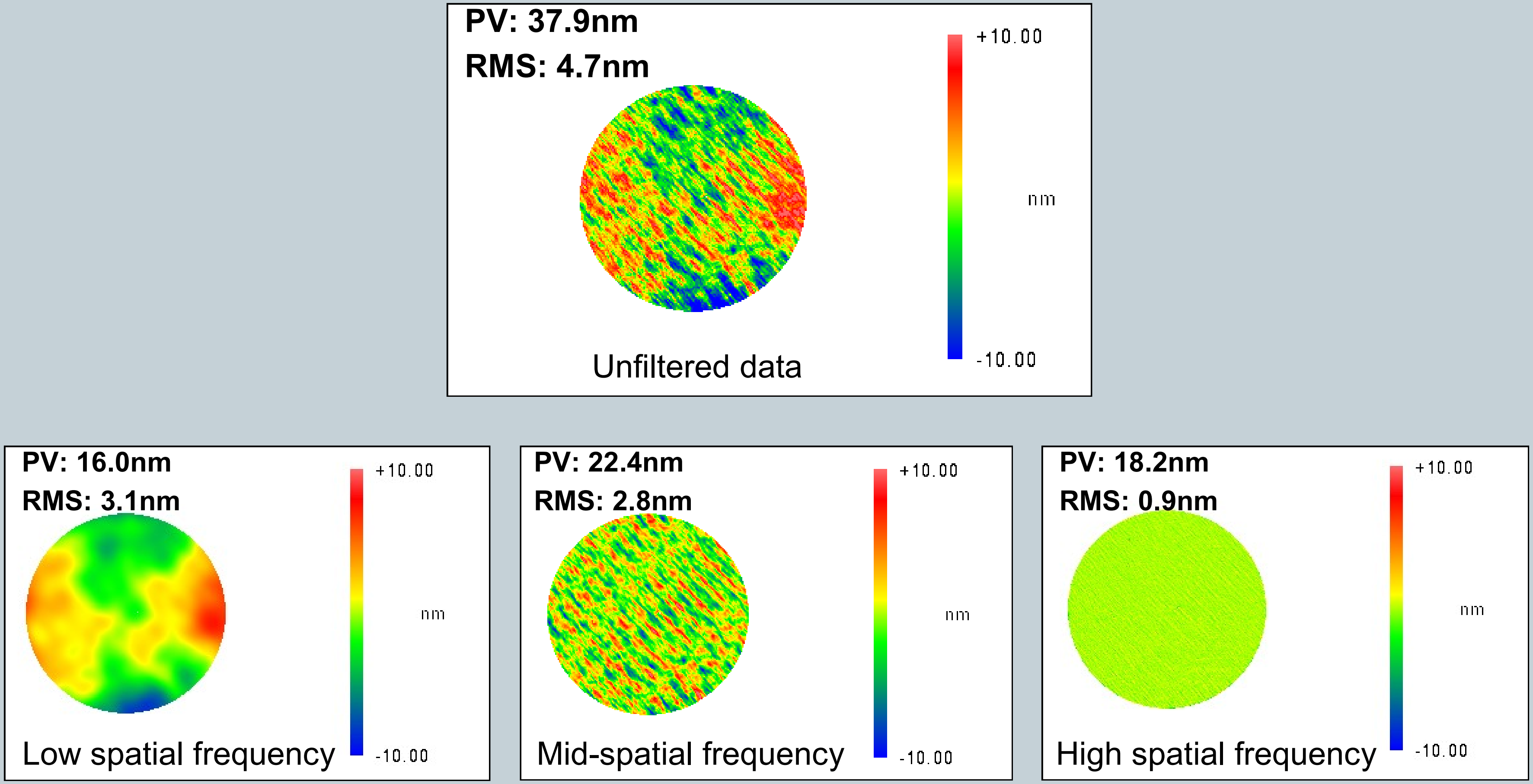
Mid-spatial frequency

PV: 17.1nm
RMS: 0.6nm



High spatial frequency

Example: Raster Errors



How Is Surface Ripple Reduced?

- Improved tool path algorithms
  - Available through ongoing software upgrades
    - Optimized tool path overlap region
    - Random tool paths (more information in David Walker's presentation)
- Adjusting slurry mechanics and chemistry at the tool/surface interface, where possible
  - Abrasive property selection example: nanodiamond friability
- Final randomized smoothing step directly after deterministic finishing
- Ensure that there are no periodic "noises" in the system
  - Machine frequency, slurry pulsations, etc.

Section 2: Mid-spatial frequencies

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  - How it is formed
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- Mid-spatial frequencies
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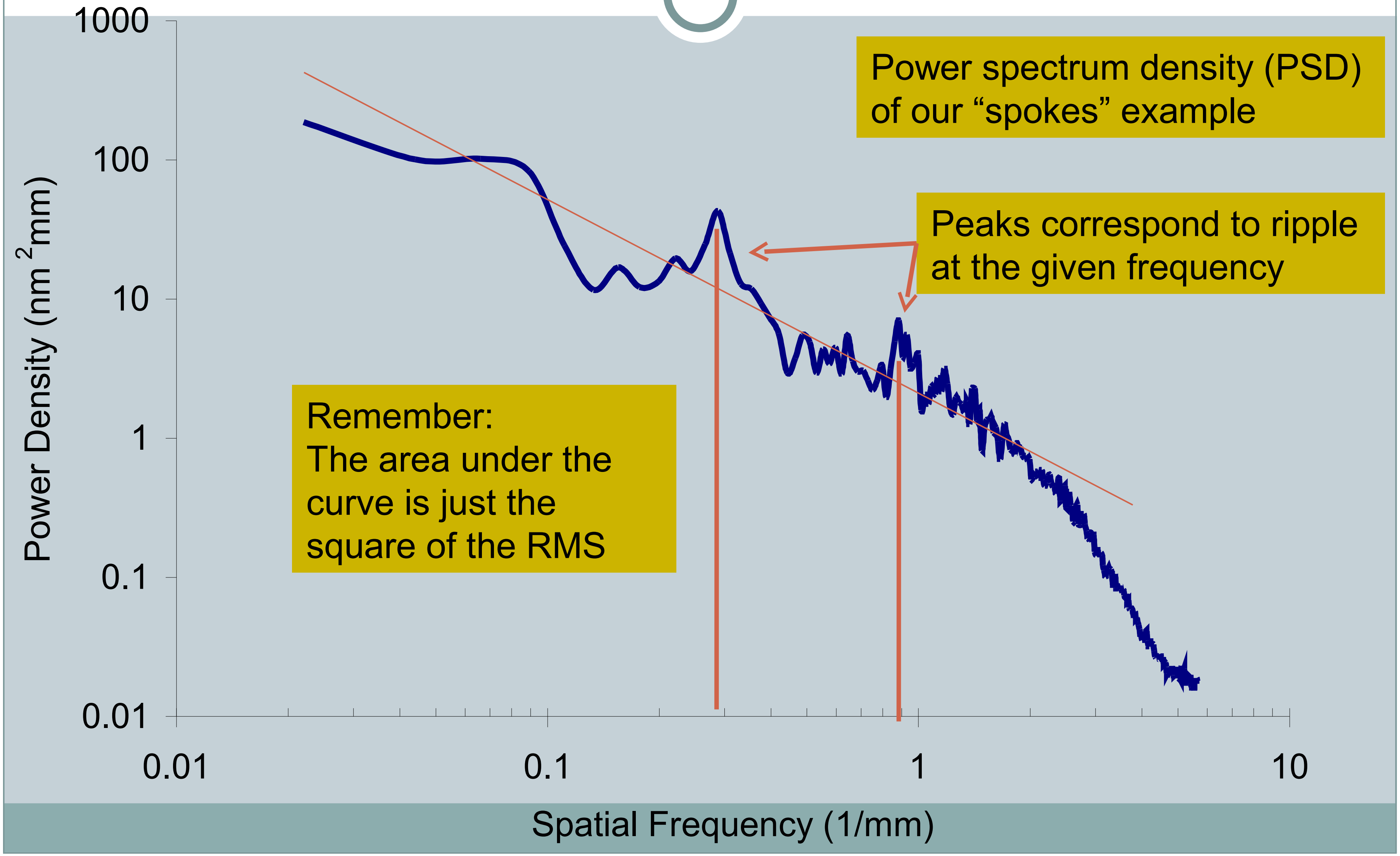
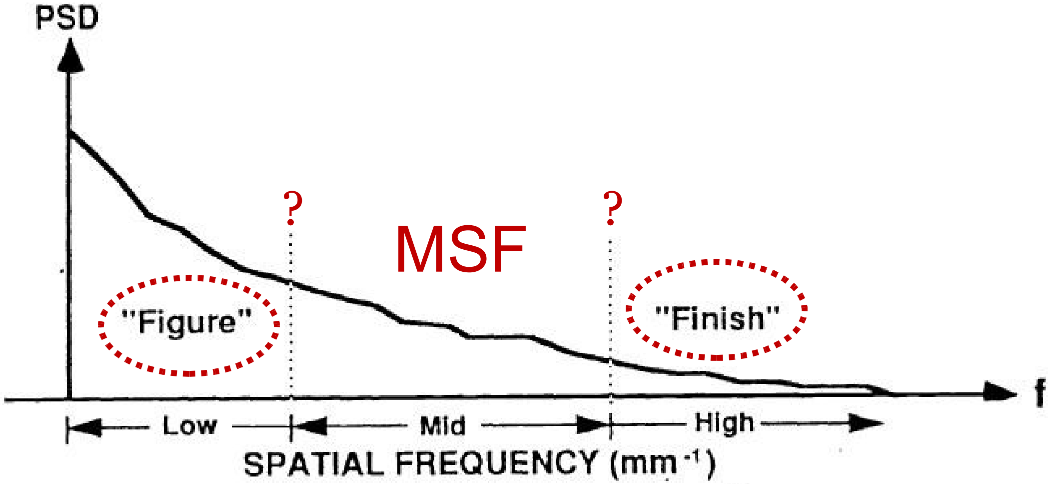
PSD signatures indicate surface ripple



What is “mid-spatial frequency”?



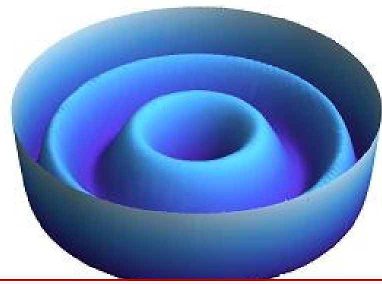
J.E. Harvey and A. Kotha, “Scattering effects from residual optical fabrication errors, Proc. SPIE 2576-25

We let the application determine the range of mid-spatial frequency band

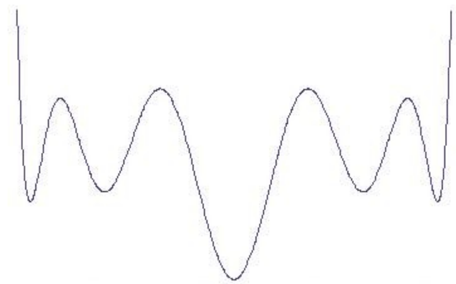
- Since the MSF band is defined by subtraction, there can be no single definition of the "mid-spatial frequency"
- Fabrication-based definition: MSF periods are
  - Too short to correct with deterministic figuring
  - Too long to ignore
  - Typically from 2 mm to about 0.2 mm
- Physics-based definition: MSF periods are
  - Long enough for wave front to be preserved in the imaging system?
  - Short enough that statistical calculation methods are valid?
- Application-based definition: MSF periods are
  - The range of periods where periodic features will interfere with the performance of the optical system, but which cannot reasonably be specified/controlled through Zernike terms

Figure is typically characterized by Zernike polynomials

Quaternary Spherical

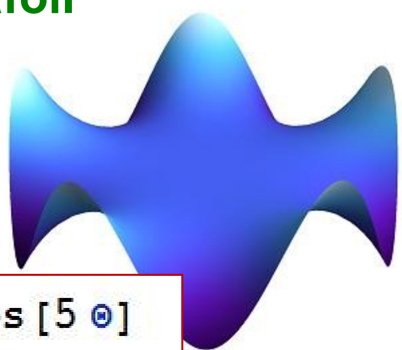


$$-1 + 30\rho^{2} - 210\rho^{4} + 560\rho^{6} - 630\rho^{8} + 252\rho^{10}$$

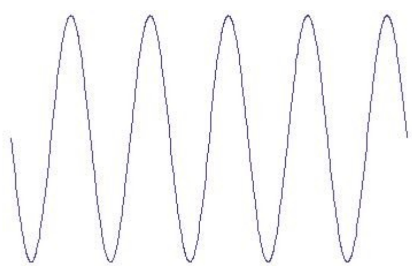


Scan profile through the center point

Pentafoil

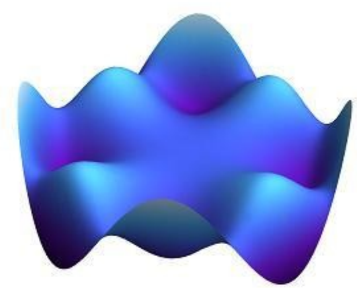


$$\rho^{5}\,\mathrm{Cos}[5\,\theta]$$



Scan profile around the edge

Secondary Tetrafoil



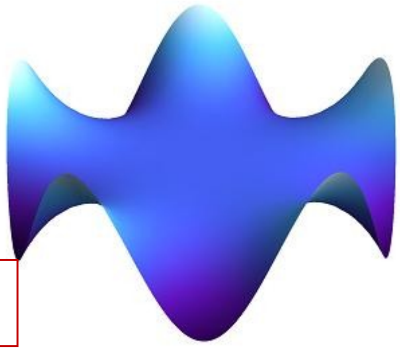
$$\rho^{4}\,(-5 + 6\rho^{2})\,\mathrm{Sin}[4\,\theta]$$

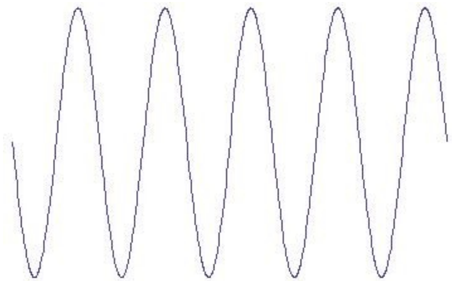
See http://wyant.optics.arizona.edu/zernikes/zernikes.htm

A general definition of mid-frequency lower boundary can be obtained with standard Zernike terms

Pentafoil

$\rho^5 \text{Cos}[5\,\theta]$

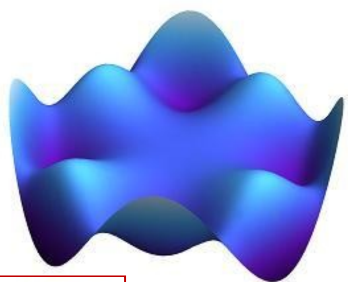


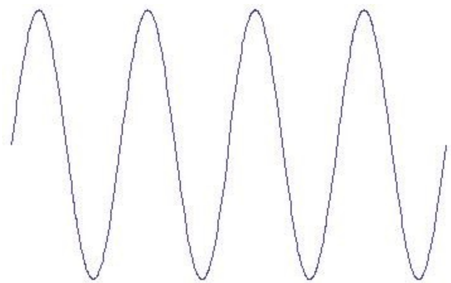


Azimuth scan at full aperture

Secondary Tetrafoil

$\rho^4 \left(-5 + 6\,\rho^2\right) \text{Sin}[4\,\theta]$





Azimuth scan at full aperture

Spatial frequencies are ≤ 5 cycles over the aperture

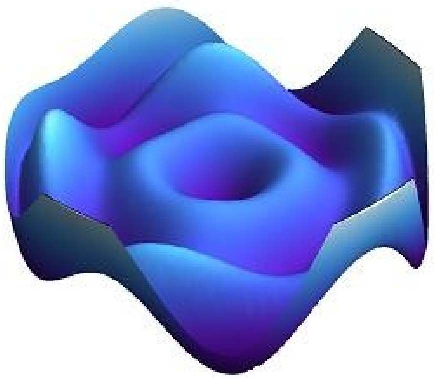
See http://wyant.optics.arizona.edu/zernikes/zernikes.htm

A general definition of mid-frequency lower boundary can be where Zernikes are becoming impractical

Can define MSF range beginning with the highest terms in the "standard" Zernike expansion (up through quaternary spherical, for instance)

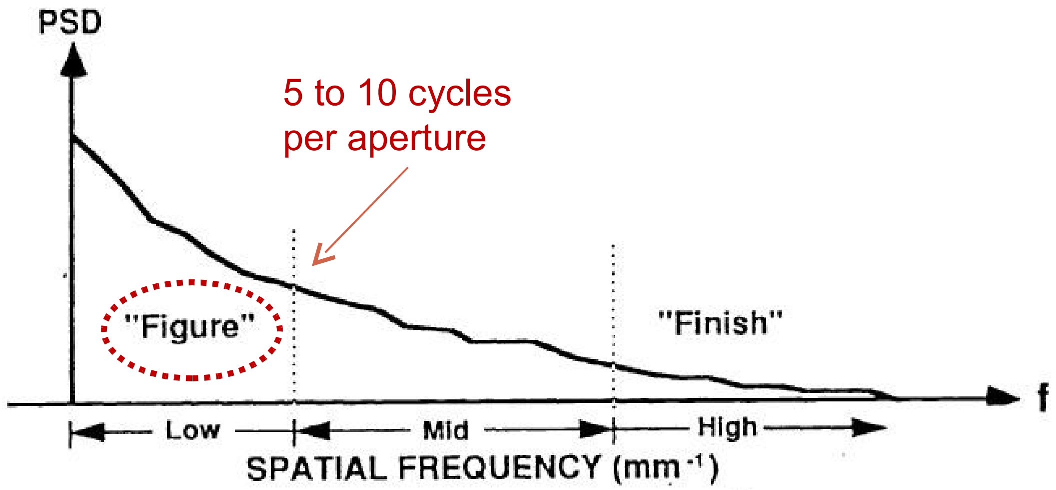
Spatial frequencies are ≤ 5-10 cycles over the aperture (with different coefficient signs and nodes/peaks not lining up)

Combination of Quaternary
Spherical, Pentafoil,
and Secondary Tetrafoil



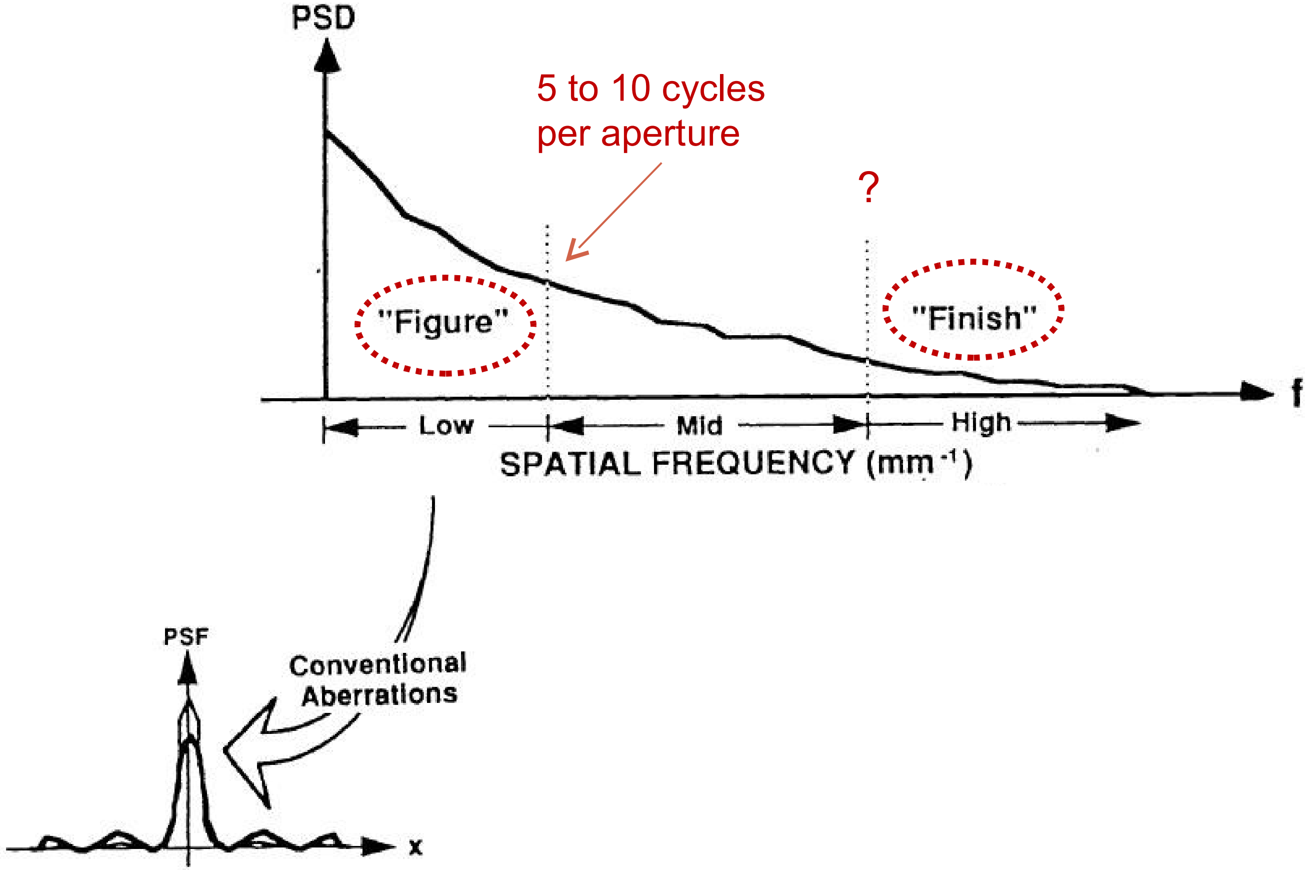
See http://wyant.optics.arizona.edu/zernikes/zernikes.htm

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



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

Finish (a.k.a “gloss” or “roughness”) is typically less critical as it results in total transmission loss



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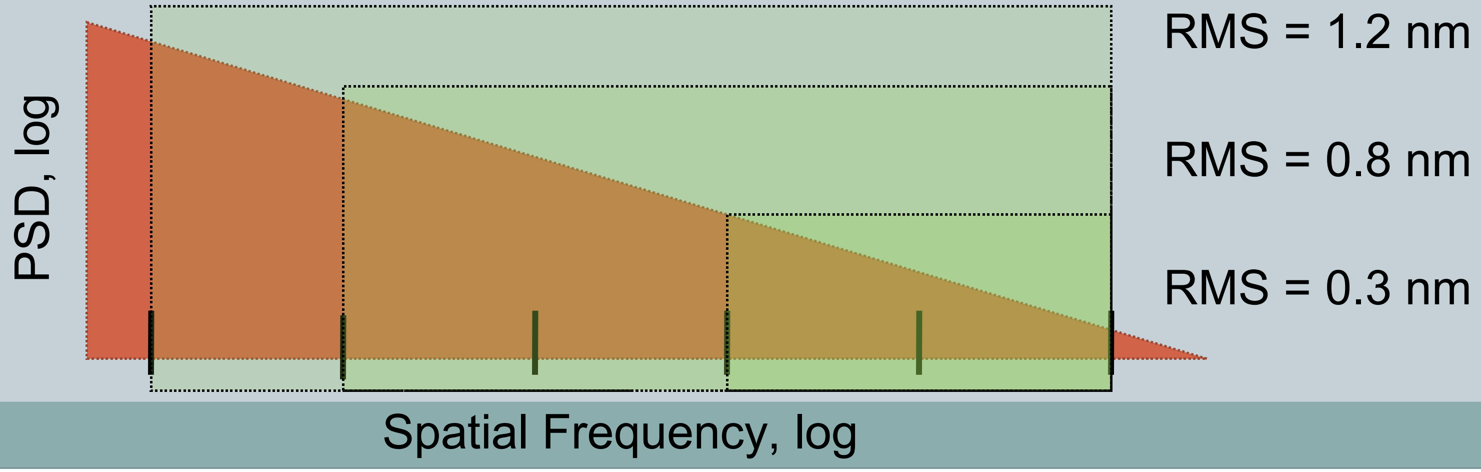
Surface finish (a.k.a roughness, gloss) and spatial frequencies

- As a loss term, controlling roughness is rarely critical to the system performance
- Typically controlled with an RMS roughness specification
- *RMS is proportional to square root of area of PSD*
  - *In other words, RMS is a function of the spatial frequency limits*
- An RMS roughness specification without a spatial frequency limit is MEANINGLESS!



Calculating the higher frequency limit of the mid-spatial frequency domain

- Define the Fresnel number* of a given spatial period (a) as

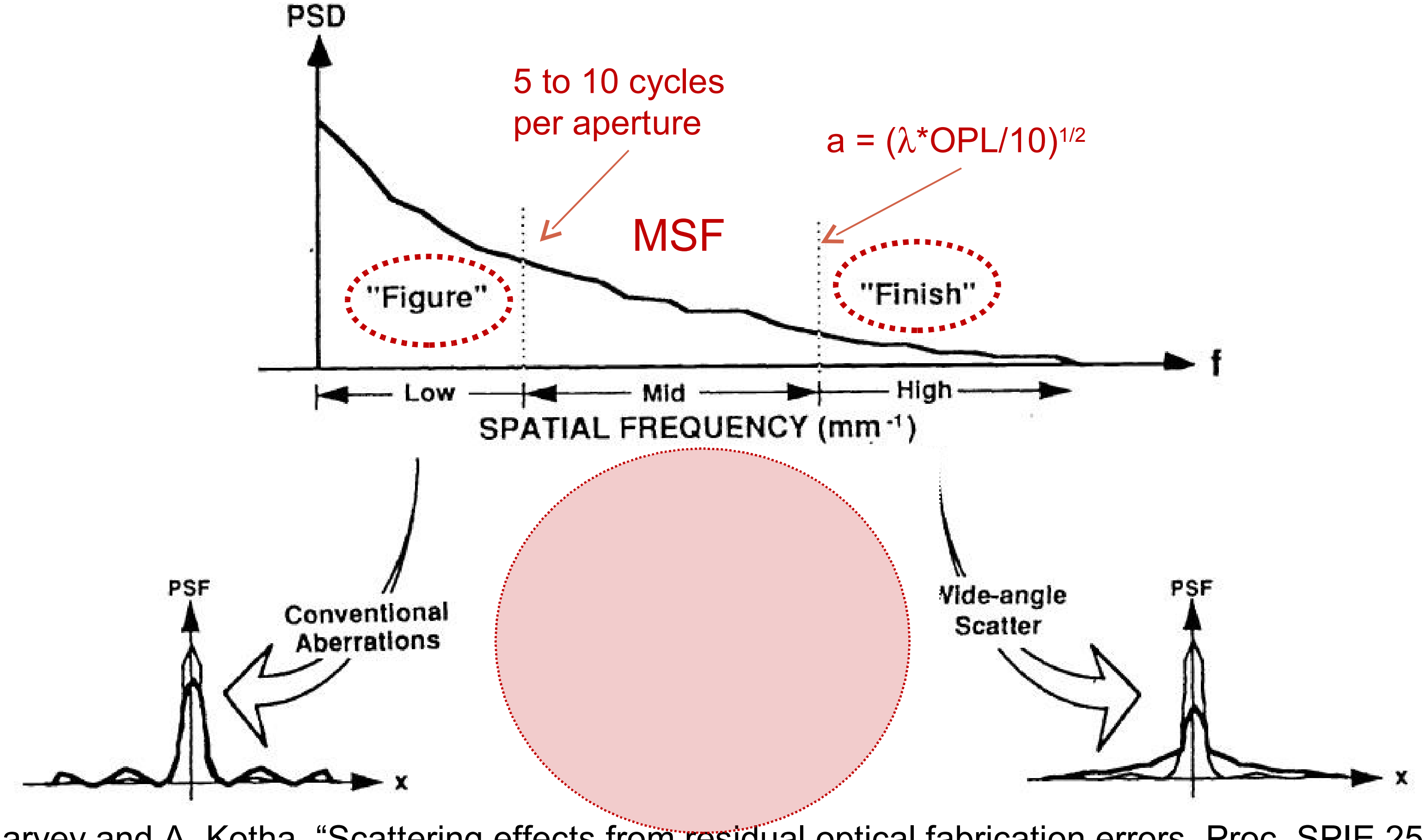
$$F = a^2/L\lambda$$

- If the propagation distance (L) from the error source to the measurement plane is large with respect to a^2/λ, the Fresnel number is small and we are considered to be in the far-field for a phase error of that frequency, and the PSF cannot be effected by changes in amplitude of the phase error
- A safe limit is if $F < 0.1$
- In other words, the boundary between roughness and mid-spatial frequency errors is when the spatial period a is:

$$a = (\lambda * OPL/10)^{1/2}$$

* Fresnel number is strictly defined as applying to the size of a diffracting aperture.

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



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

Section 3: Specification of mid-spatial frequency ripple

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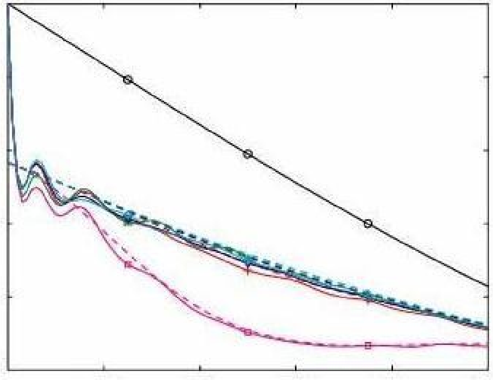
Estimating MSF effect on performance: first-order effects

Energy lost from the central PSF lobe (diffraction-limited imaging system):

$$S = S_0 \exp\left[-\frac{4\pi^2}{\lambda^2}\sum_i (n_i - n_i')^2 \sigma_i^2\right]$$

σ_i^2 is the mean square mid-spatial-frequency error of surface i.

S_0 is the Strehl ratio for the nominal system (including low-spatial-frequency surface errors)



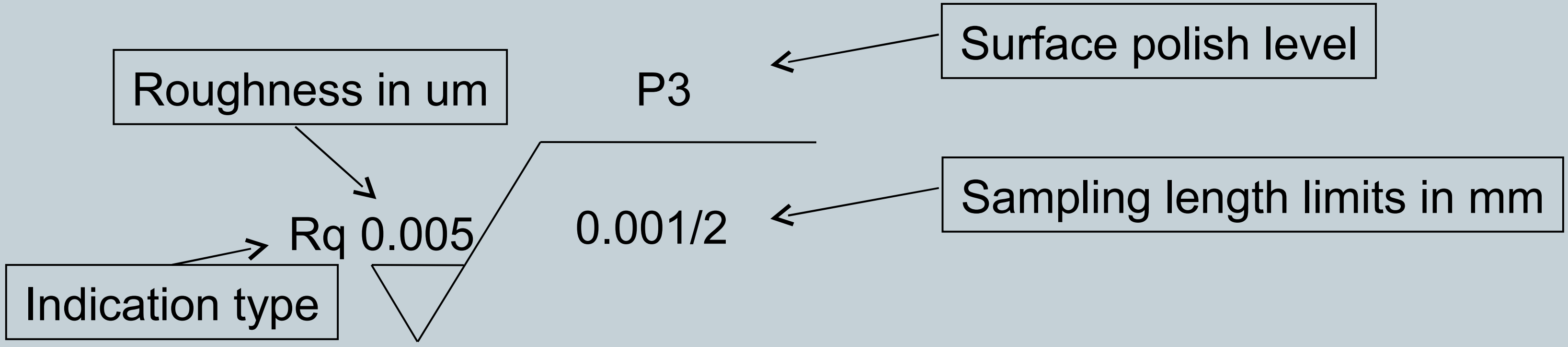
R. N. Youngworth and B. D. Stone, “Simple estimates for the effects of mid-spatial frequency surface errors on image quality”, Applied Optics 39(13)

The simplest notation for mid-spatial frequency ripple is found is ISO 10110

- ISO 10110, published in 1996, is the international optics drawing standard
  - Gaining increasing popularity in Europe and Asia
  - Soon to be made the national drawing standard for the USA
- Part 8, called surface texture, provides all the notations for any global, statistical specification of surface shape
  - Roughness of matte surfaces
  - Roughness of specular surfaces
  - Micro-defects
  - Mid-spatial frequency ripple
  - Power spectral density
- Shown using a “square root” sign with the tip at the surface being indicated

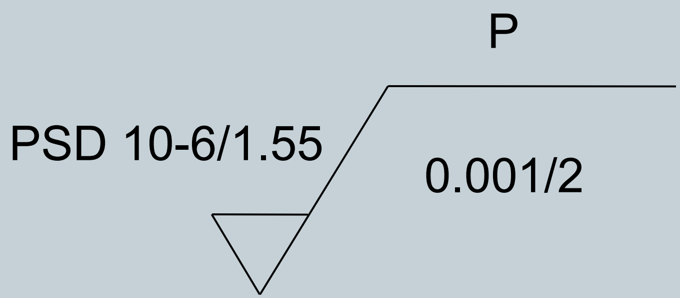
ISO 10110-8 drawing notation

- References ISO 4287 and ISO 1302 for statistical properties of surfaces
- No (explicit) limit to the number of texture callouts versus region or spatial period
  - Many people use two or more for complex surface requirements.
- Typical notation:



- Can also indicate a range of roughness values: Rq max/min

If desired, it can also be used for Power Spectral Density



- Surface PSD < 1 x 10^{-6} $p^{1.55}$ for spatial periods (p) from 0.001 mm to 2 mm, in units of mm^3
- Presumes a 1D profilometer trace verification
- The units are a bit squirrely; I prefer nm^2 mm (expected in 2009 version)

Section 4: Summary

- From a spatial frequency point of view, surface form errors are a continuum.
  - Figure
  - Roughness
  - Mid-spatial frequency errors.
- The boundaries between these regions are defined by the application.
- MSF ripple can be defined as extending from
  - a = 5-10 cycles per aperture
  - $a = (\lambda * OPL/10)^{1/2}$
- Amplitudes can be calculated from a Strehl ratio budget
- Notations exist in ISO 10110 to allow clear specification of MSF ripple amplitude and spatial frequency