High Spatial Resolution Metrology using Sub-Aperture Stitching

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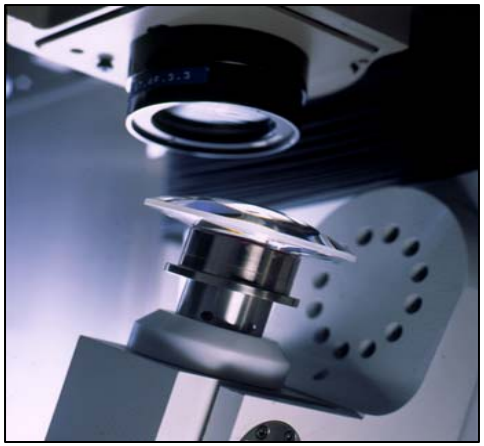
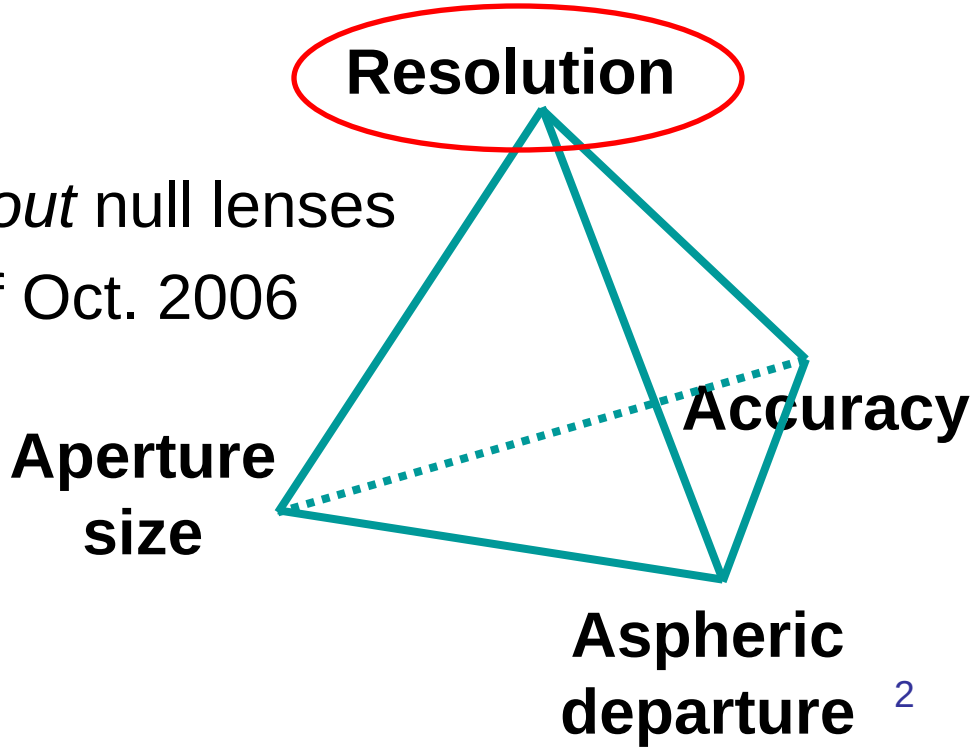
Acknowledgements: Scott Antonille – NASA Goddard

Asphere metrology

Background

- SSI®:
  - Sub-aperture Stitching Interferometry
  - Introduced in 2004
  - Measure flats & spheres with increased aperture size, accuracy and resolution
- SSI-A™:
  - Asphere metrology *without* null lenses
  - Commercial reality as of Oct. 2006



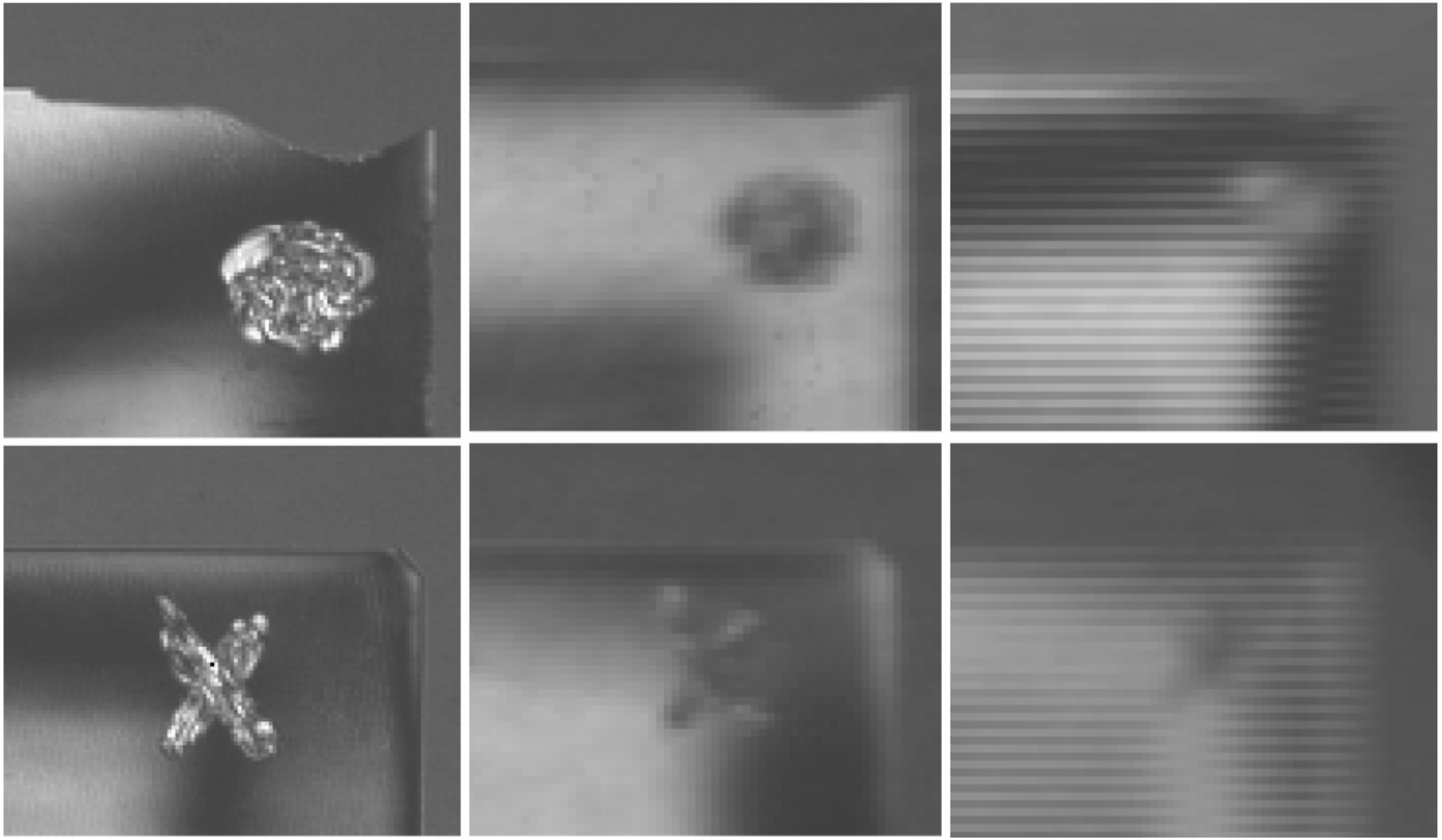


Interferometer Resolution and PSD
Background

- In the past, common metrics such as “Peak to Valley” (PV) and “rms” were sufficient for precision optics.
- Today’s more challenging applications require a more rigorous specification protocol.
- Power spectral density (PSD) is an increasingly popular method of quantifying a signal within a specific spatial band.
- One question (in)frequently asked – ***Can this instrument (interferometer) actually measure the band of interest?***

Fizeau Interferometer Resolution

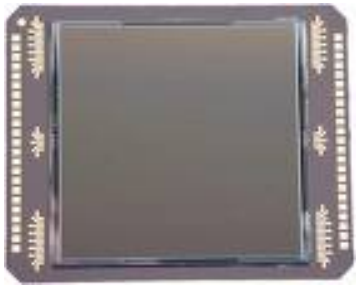
Same optic, different interferometers…

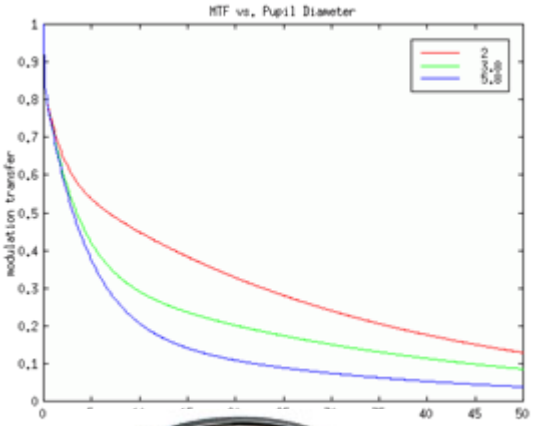


…why does this happen?

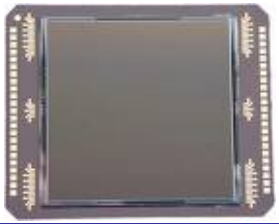
Fizeau Interferometer Resolution
Common influences

- In practice, there are 3 main issues that limit a Fizeau interferometer's *true* resolution:
  - Pixel scale - # of pixels/unit length (1K x 1K CCD are now common)
  - Interferometer Transfer Function (ITF)
  - System Bias (reference wave)



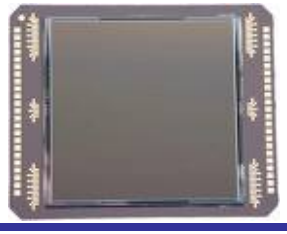


CCD's & Pixel Scale

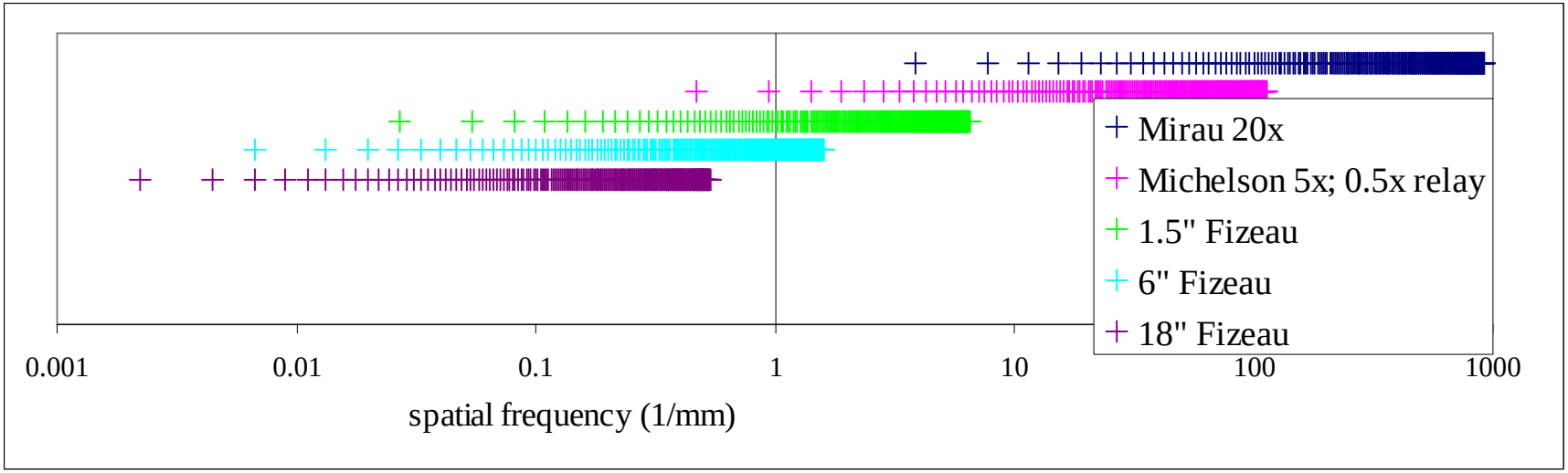


- From consumer cameras to commercial interferometers, detector technology has advanced dramatically over the last decade.
- 1 Megapixel (1K x 1K) CCD's are now common, if not standard offerings on commercially available interferometers.
- On a 6" (150 mm) aperture, that yields a *pixel scale* of 0.15 mm/pixel.

CCD's & Pixel Scale



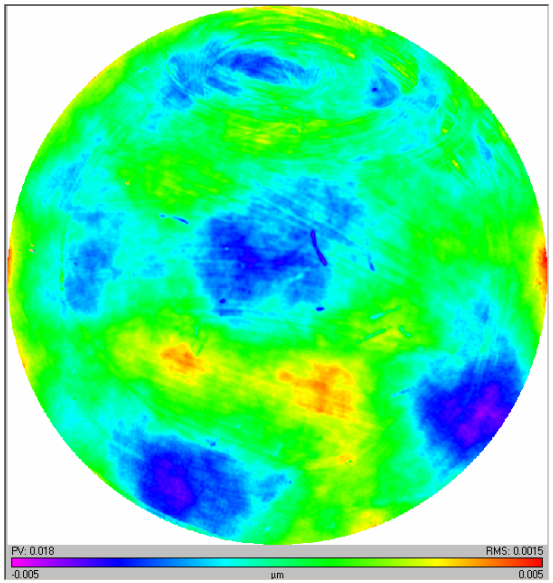
Sampling range for common measurement instruments:



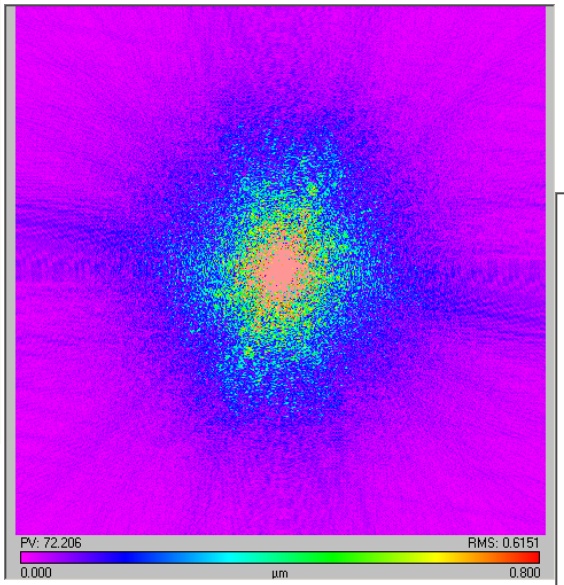
- **A 6" Fizeau w/ 1K camera yields a pixel scale of 0.15 mm/pixel.**
- **Nyquist sampling requires a minimum of 2 pixels/cycle.**
- **Can we actually measure 0.3 mm features?**

Interferometer Transfer Function
PSD Calculation Process

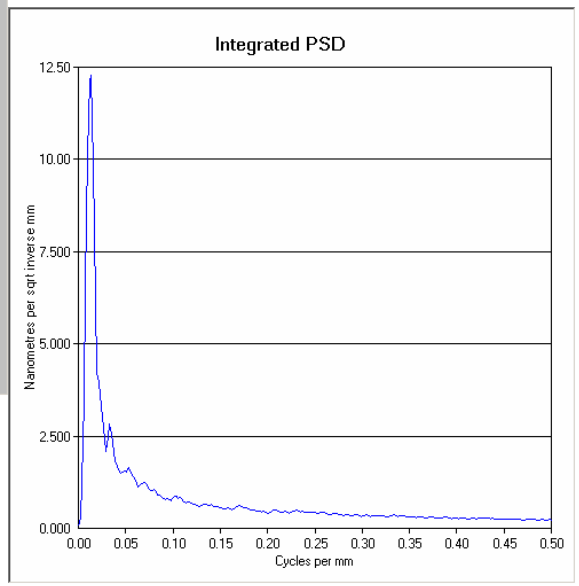
1. 3-d Phase map (Z(x,y))



2. FFT (Z'(1/x,1/y))

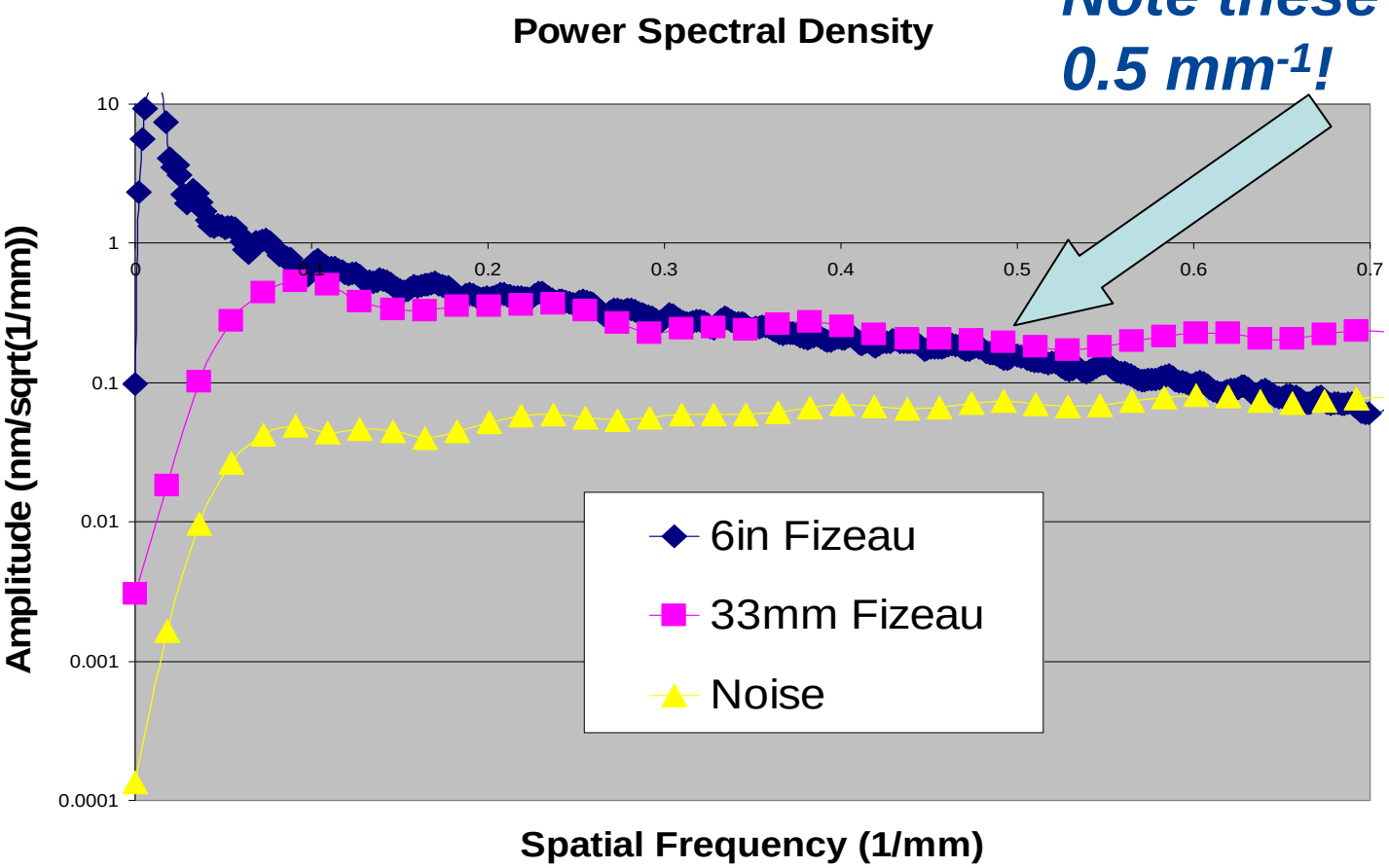


3. Integrated PSD (2-d)



Interferometer Transfer Function
Actual PSD Plots

Note these plots cross at 0.5 mm^{-1}!



Nyquist limit

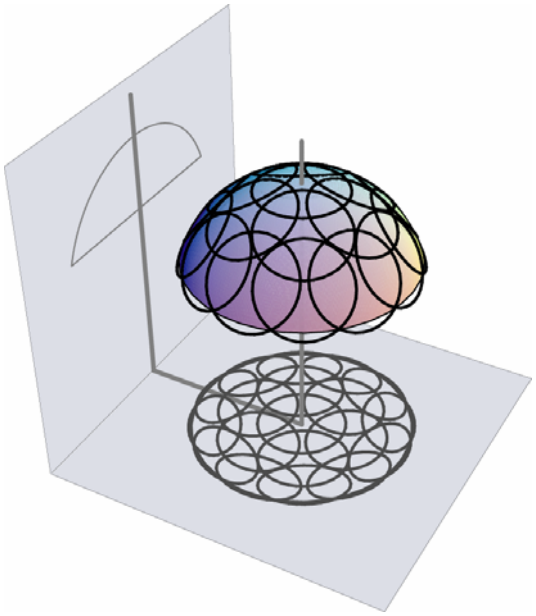
6" = 3.3 mm^{-1}

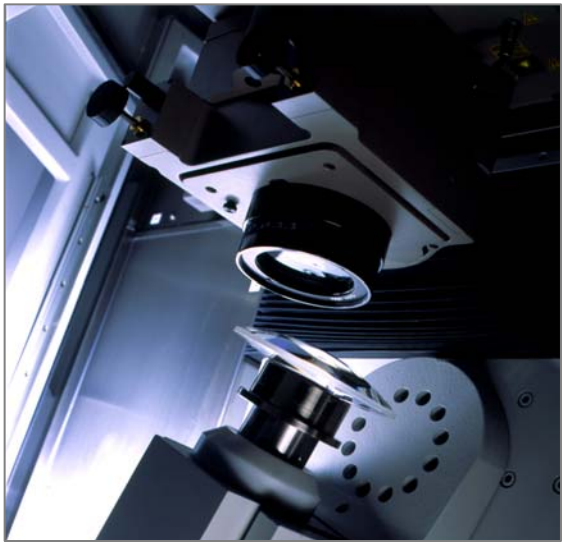
33mm = 10 mm^{-1}

****The low magnification (6") system's ITF drops to the noise floor at only 20% of the Nyquist limit!***

Interferometer Transfer Function
Stretching the ITF

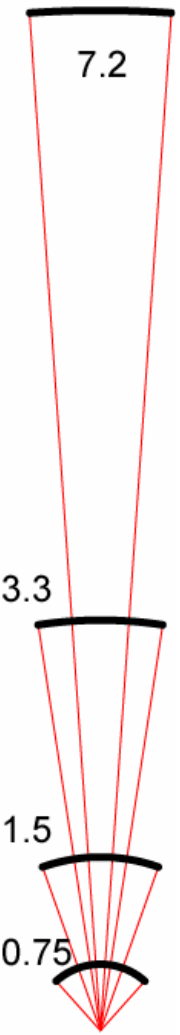
- *Goal:* We want to increase the lateral resolution without sacrificing low spatial frequency data.
- *Solution:* Use higher magnification test in conjunction with sub-aperture stitching.



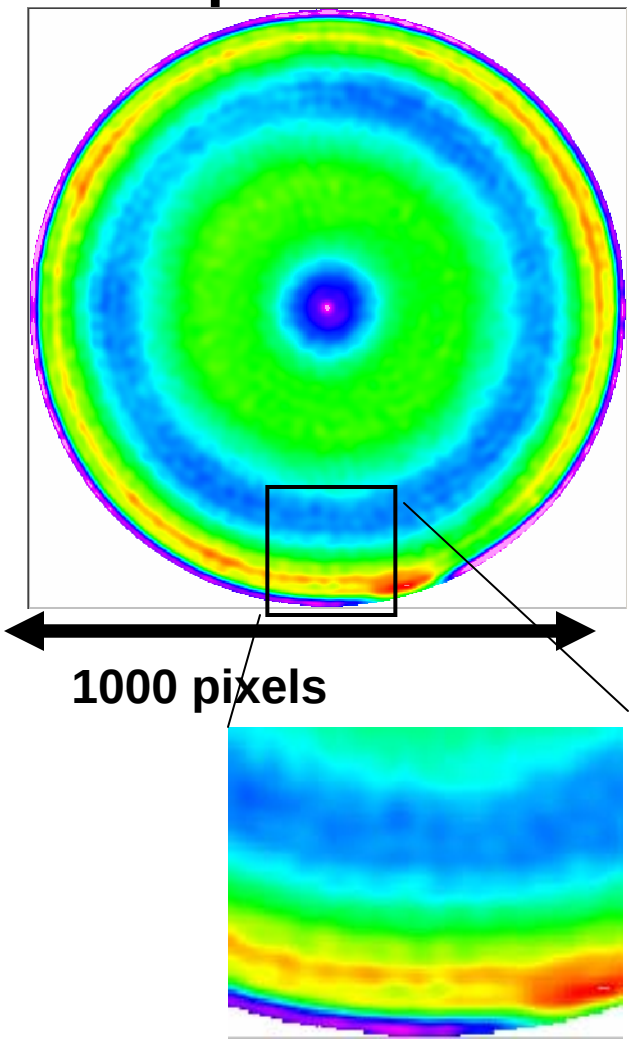


Interferometer Transfer Function

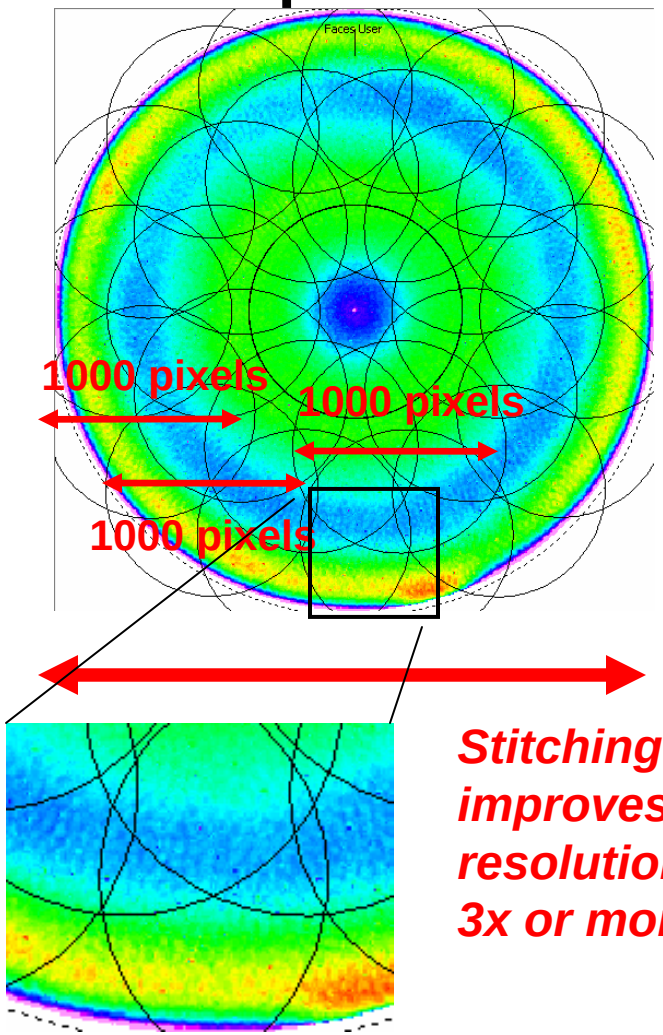
Stretching the ITF



Full aperture test



Subaperture Test

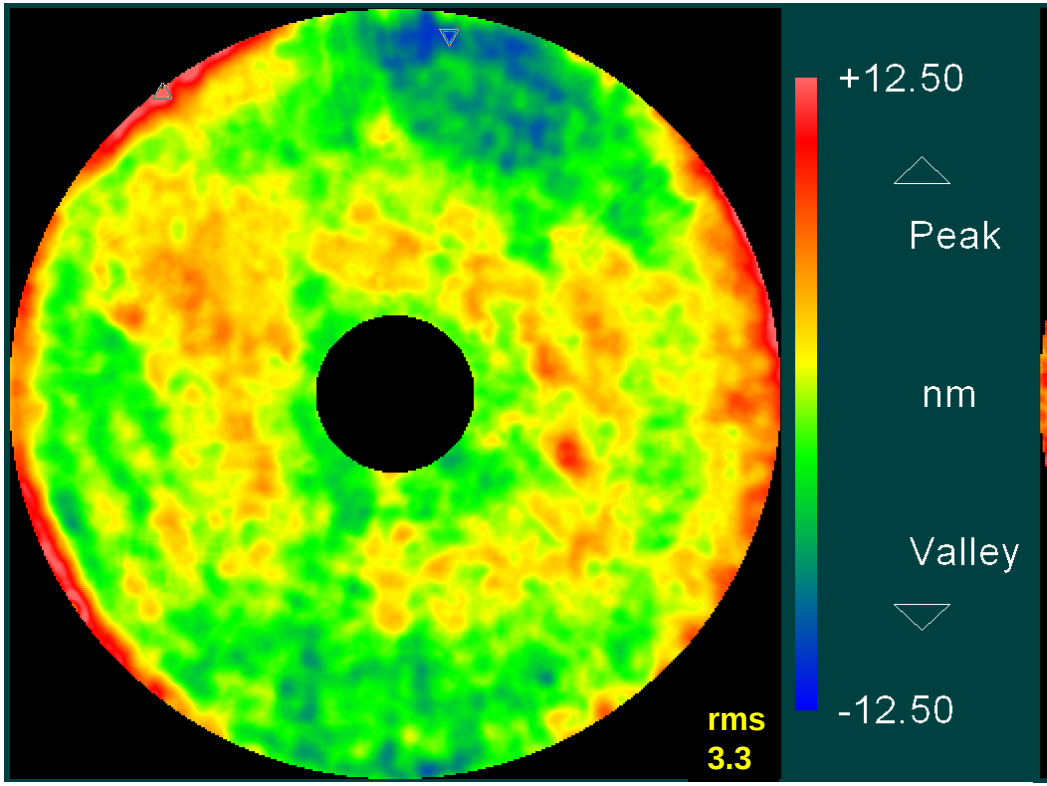


Stitching improves resolution by 3x or more!

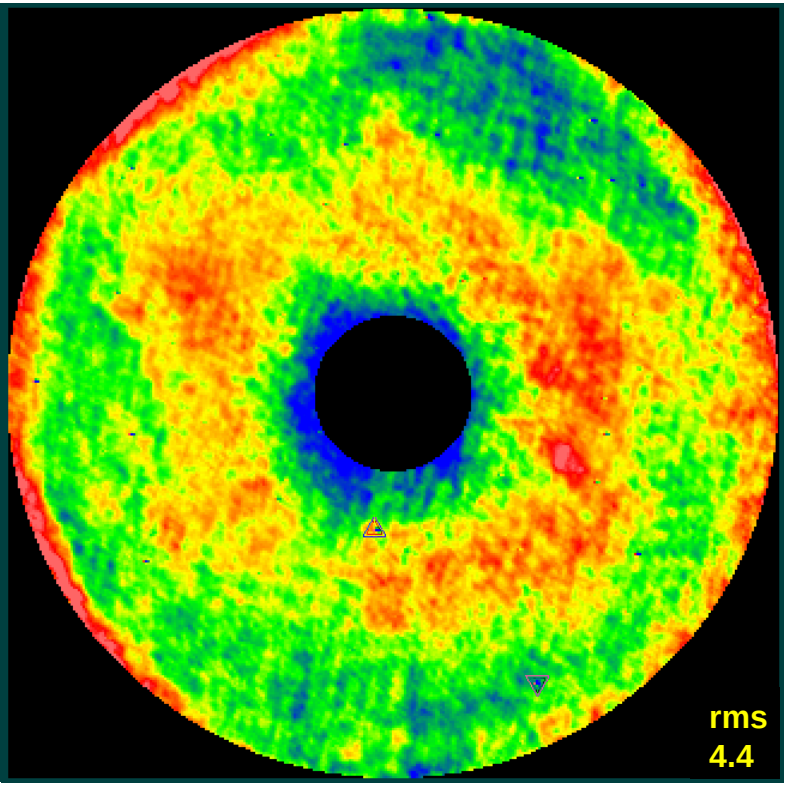
Interferometer Transfer Function
Stretching the ITF

- Example: High precision asphere:

Null test (conic w/ retro-sphere)



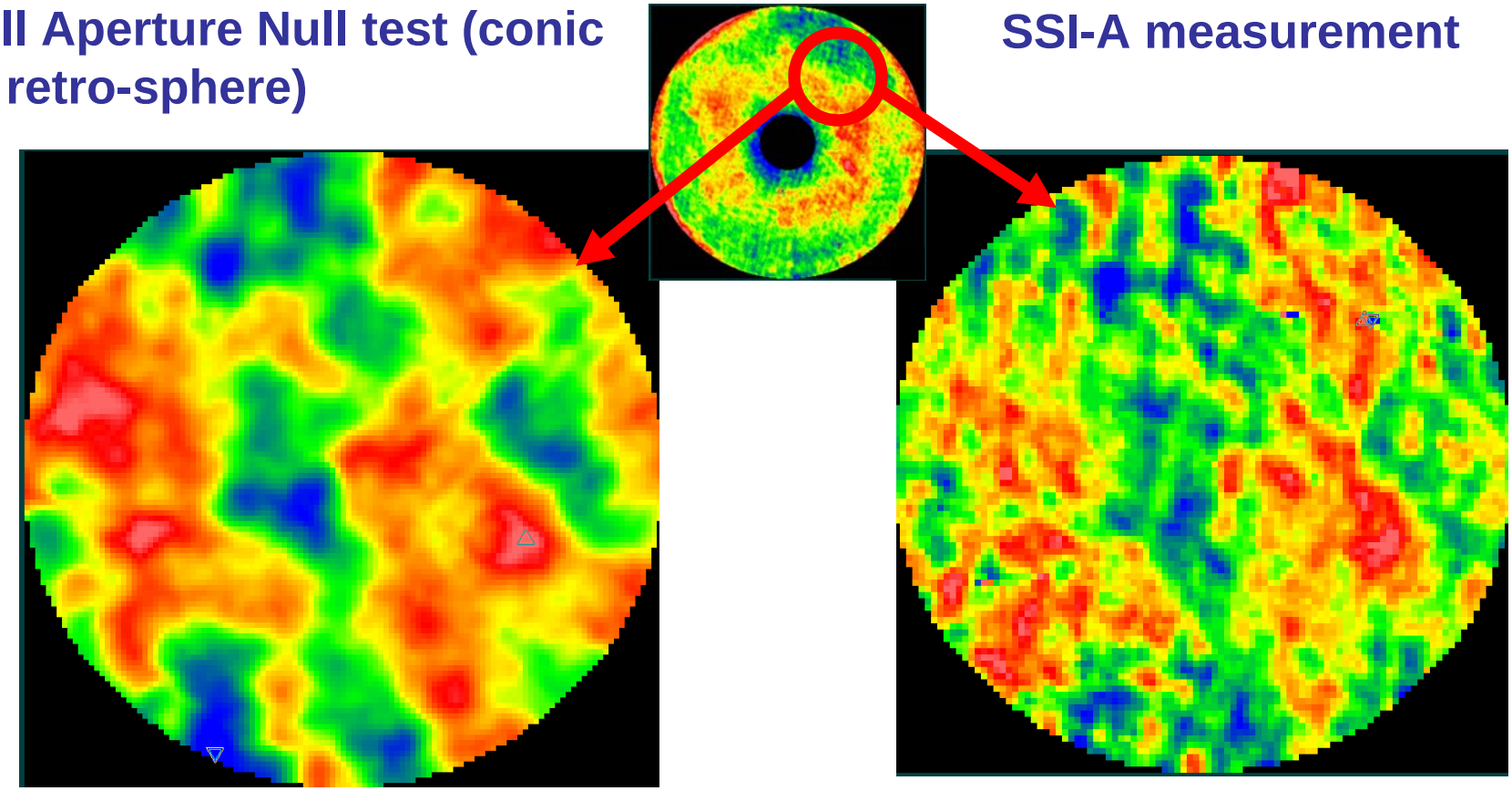
SSI-A measurement



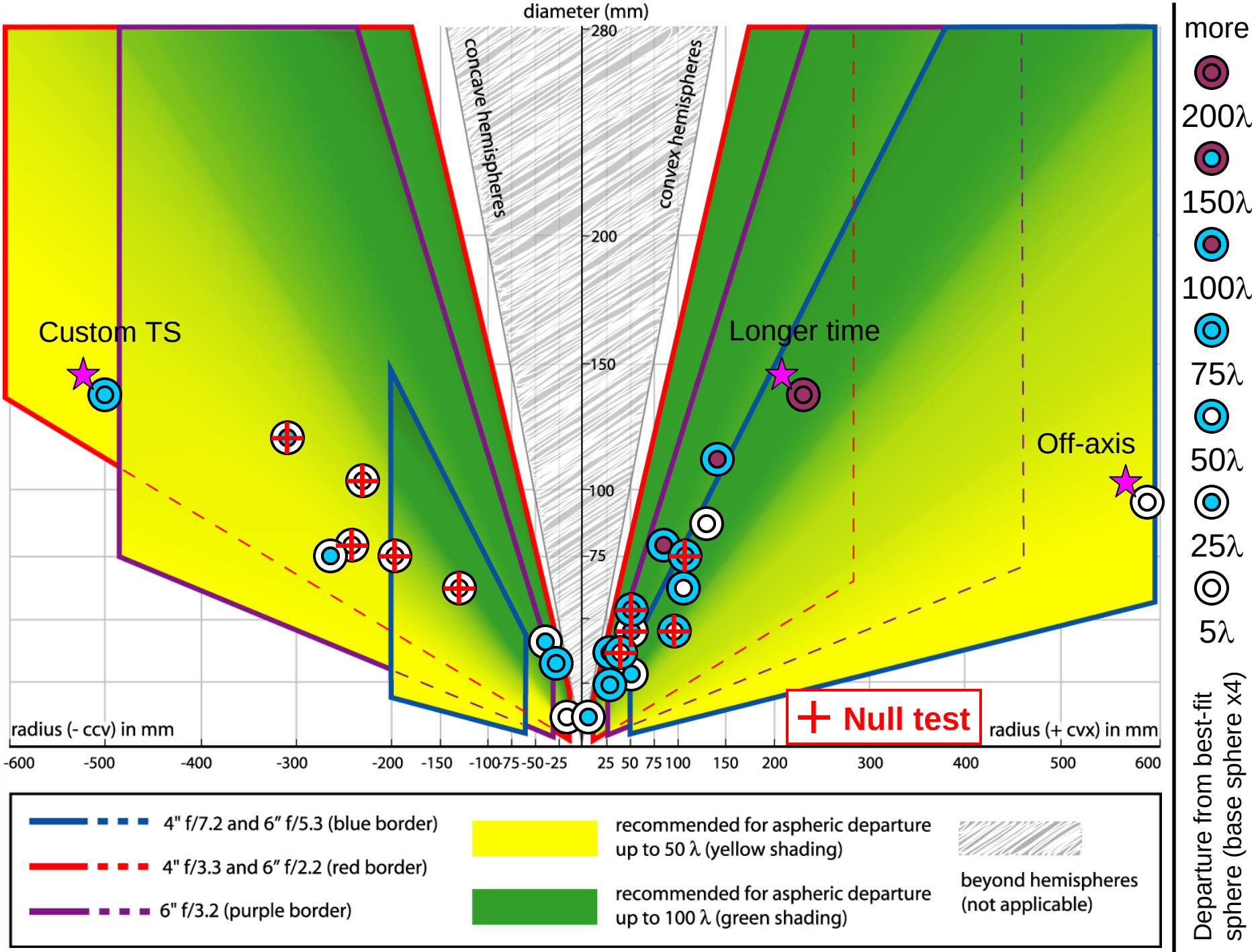
Interferometer Transfer Function
Stretching the ITF

- Example: High precision asphere:

Full Aperture Null test (conic w/ retro-sphere)

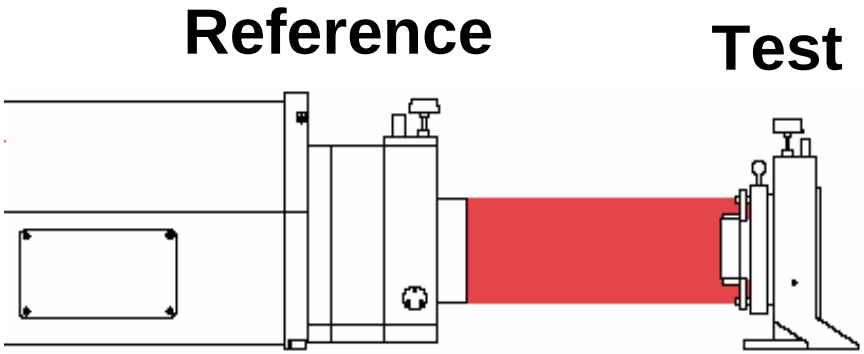


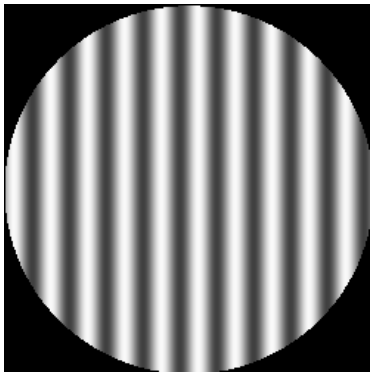
SSI-A measurement


diameter (mm)
280
200
150
100
75
concave hemispheres
convex hemispheres
Custom TS
Longer time
Off-axis
Null test
radius (- ccv) in mm
radius (+ cvx) in mm
-600 -500 -400 -300 -200 -150 -100 -75 -50 -25 25 50 75 100 150 200 300 400 500 600
more
200λ
150λ
100λ
75λ
50λ
25λ
5λ
Departure from best-fit sphere (base sphere x4)
4" f/7.2 and 6" f/5.3 (blue border)
4" f/3.3 and 6" f/2.2 (red border)
6" f/3.2 (purple border)
recommended for aspheric departure up to 50 λ (yellow shading)
recommended for aspheric departure up to 100 λ (green shading)
beyond hemispheres (not applicable)

Interferometer Resolution

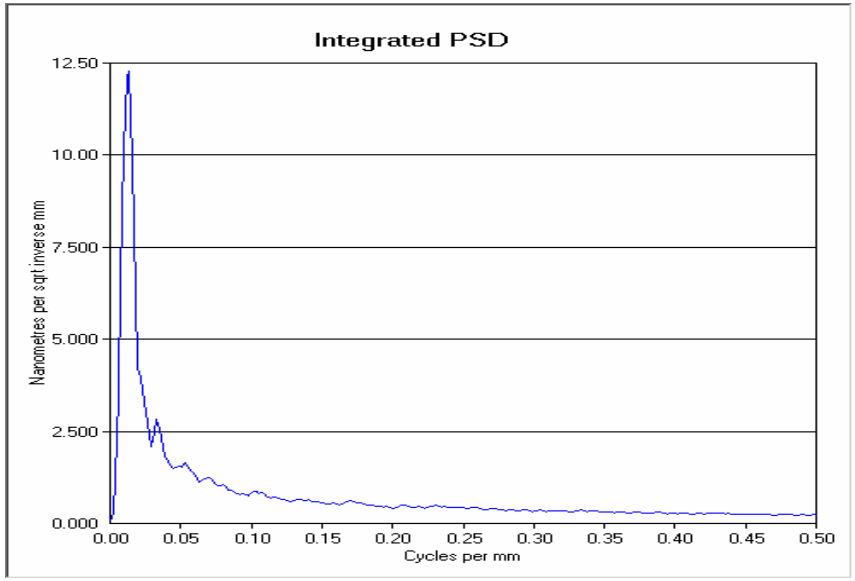
Reference wave bias has its own PSD!





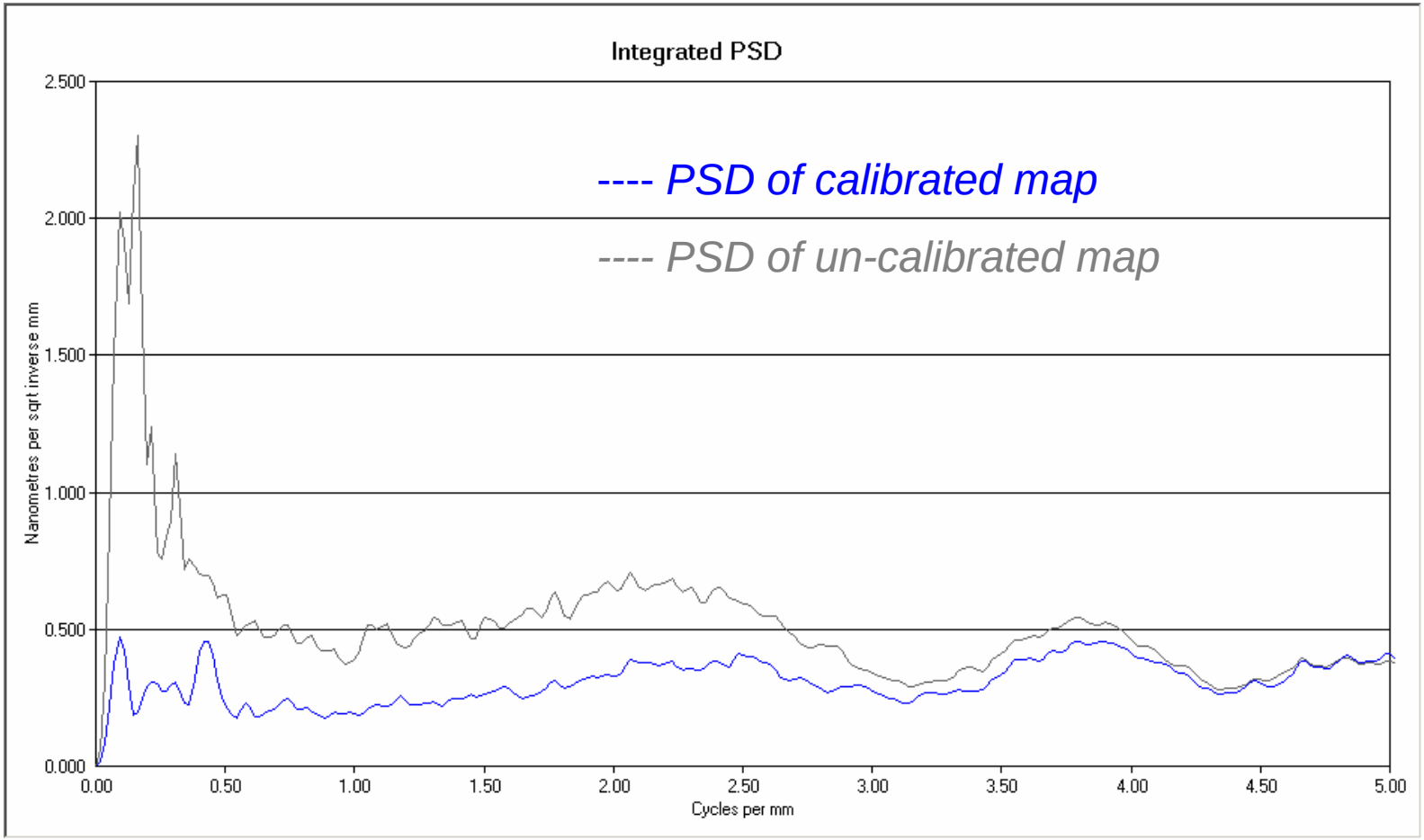
= Test + Reference

Therefore…



$$= PSD_{Test} + PSD_{Reference}$$

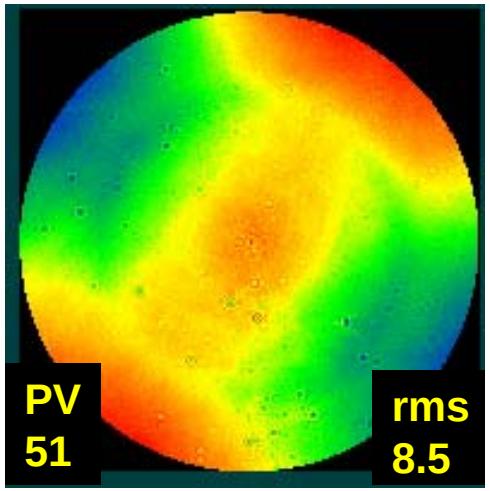
Reference wave bias
Must calibrate



The reference wave will ADD BIAS within the measurable frequency band. For PSD specifications, calibration is a must!

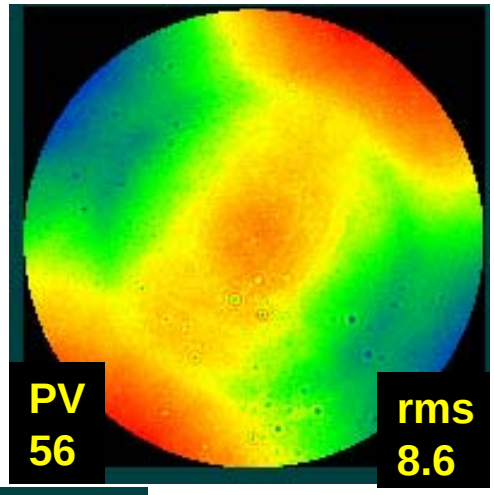
Reference wave bias
Calibration Methods

In focus

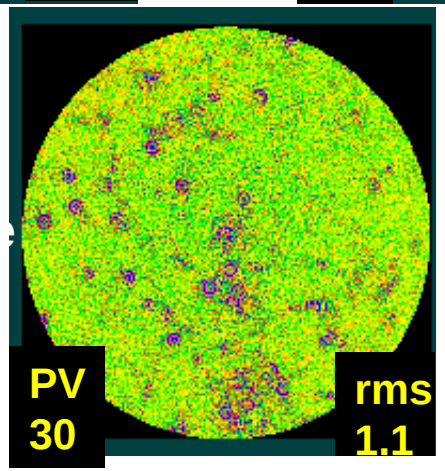


50 nm PV scale

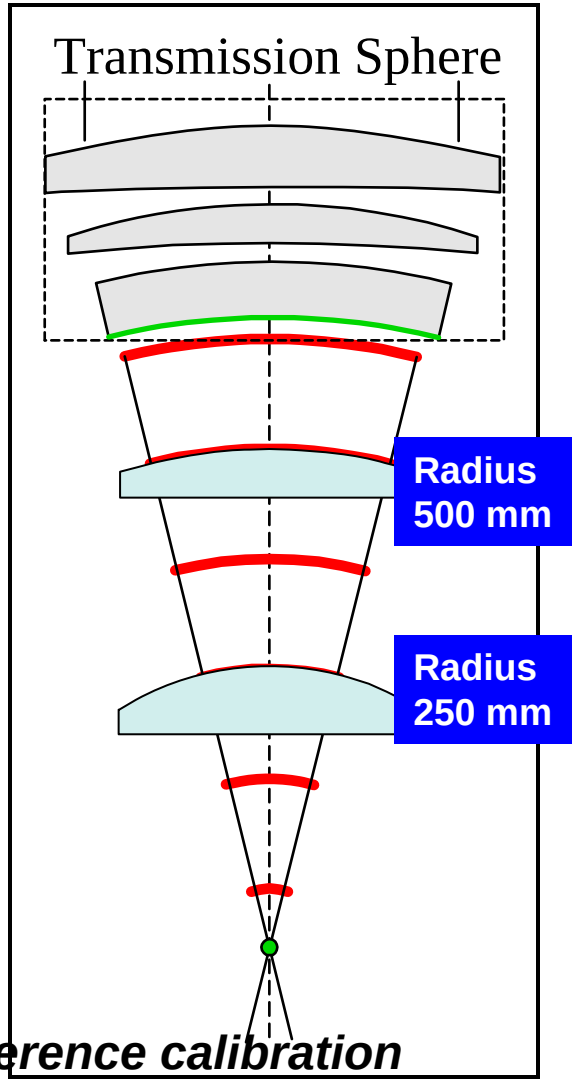
Out of focus



Difference



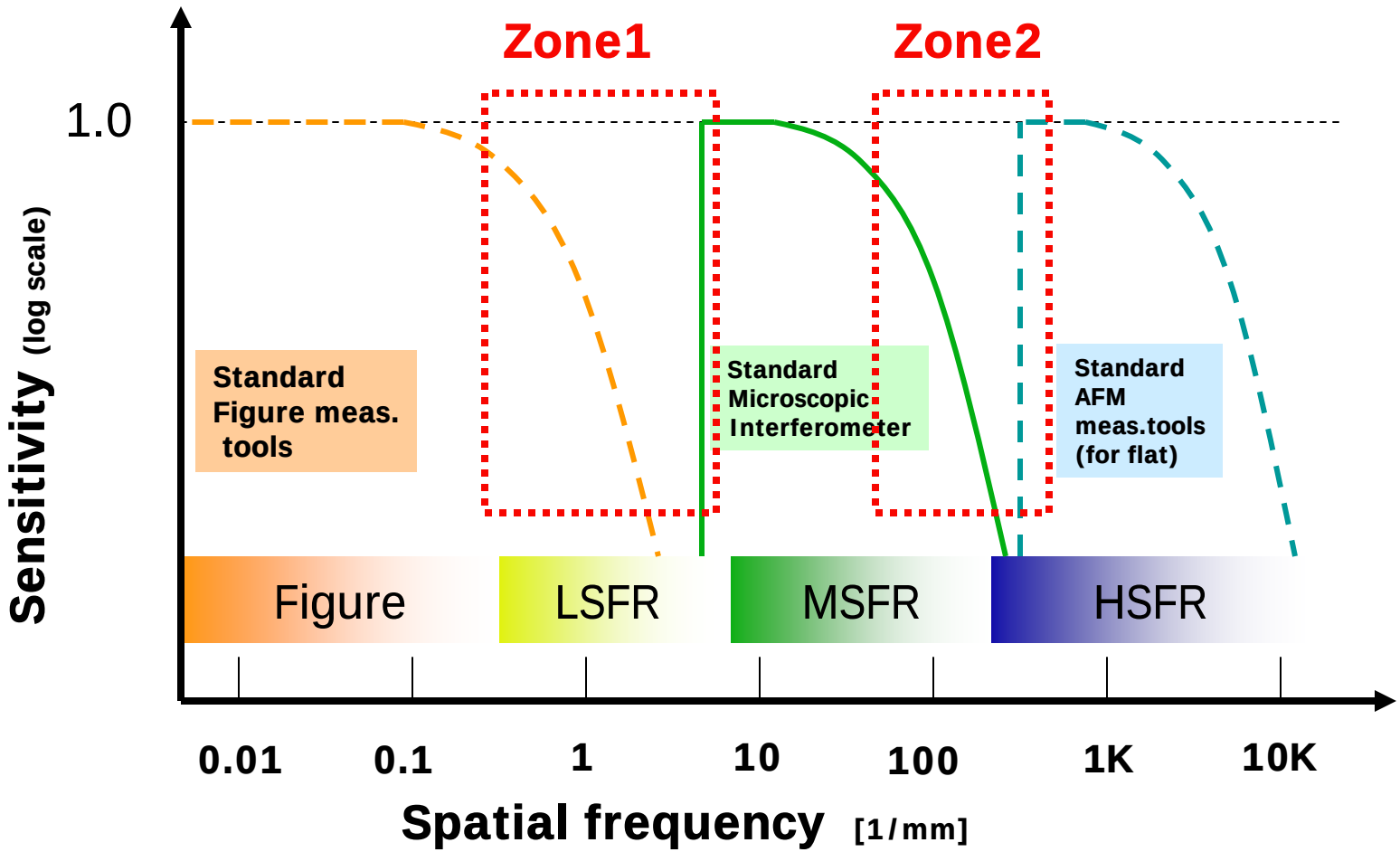
Radius 250



Accurate mid-frequency measurement requires <u>in-line</u> reference calibration

The SSI® can calibrate it <u>accurately</u> and <u>automatically</u>!

Typical Instrument Transfer Functions(ITF) of standard metrology tools on the large aspheric surface



From "Advanced Metrology Tools Applied for Lithography Optics Fabrication and Testing" by Masaru Ohtsuka, *Production Engineering Research Laboratory , Canon Inc., OF&T 2006, Invited Paper* OFWC1, *OSA.*

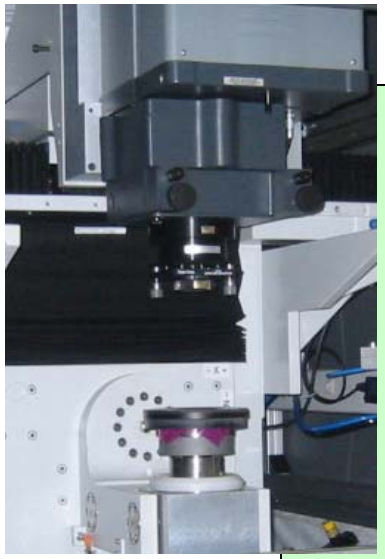
2.Low Spatial Frequency Roughness (LSFR) Measurement Tool : MFA-400

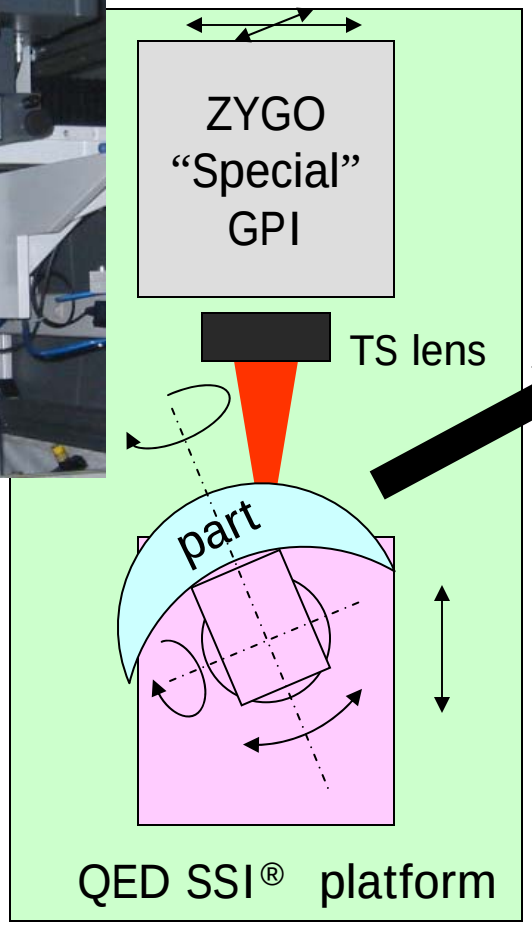
Features

- Special platform and software by QED's SSI®
- Special interferometer head by ZYGO
- Spatial frequency range: 0.3-5.0 cycles/mm
- Uncertainty:0.1nmRMS for mild asphere
- Uncertainty:0.2nmRMS for steep asphere
- Automatic measurement control software

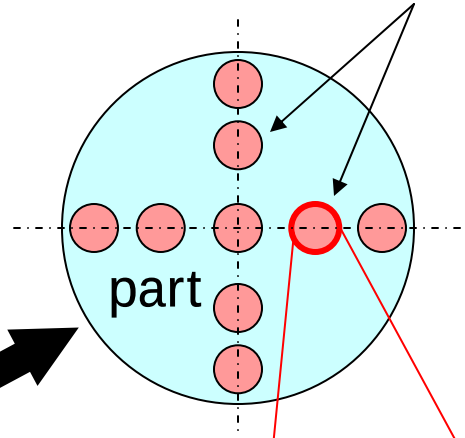
From "Advanced Metrology Tools Applied for Lithography Optics Fabrication and Testing" by Masaru Ohtsuka, *Production Engineering Research Laboratory , Canon Inc., OF&T 2006, Invited Paper* OFWC1, *OSA.*

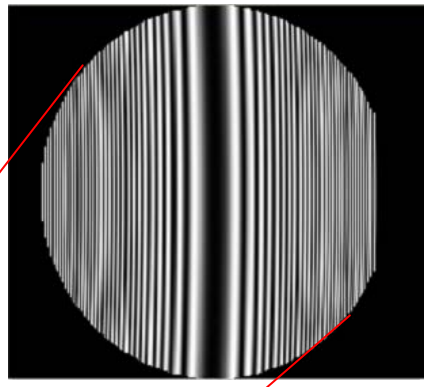
How does it work? (conceptual)

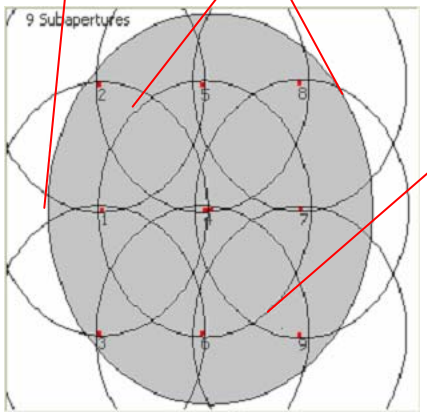




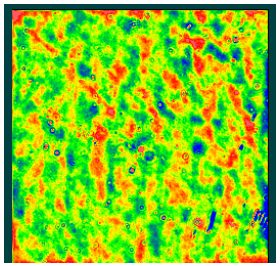
Scheduled regions to be measured







Sub aperture lattice map

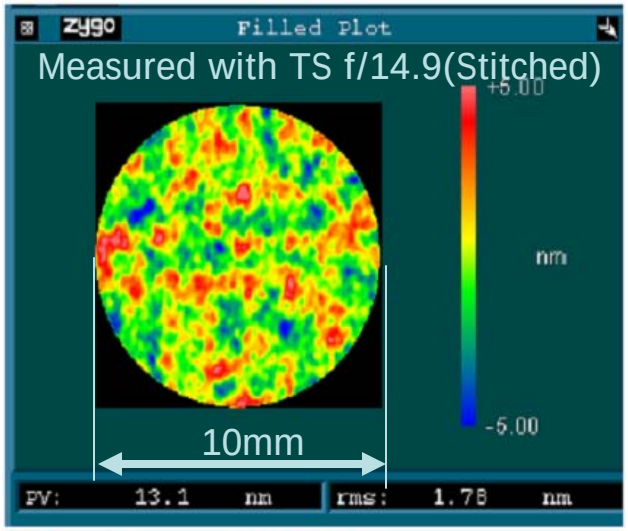


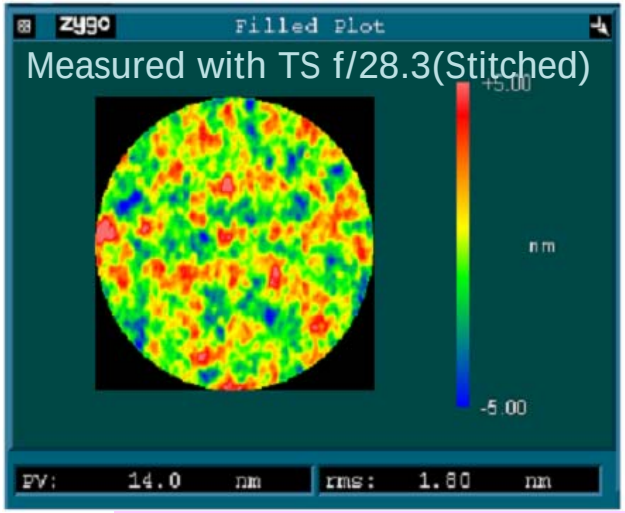
Final stitched data

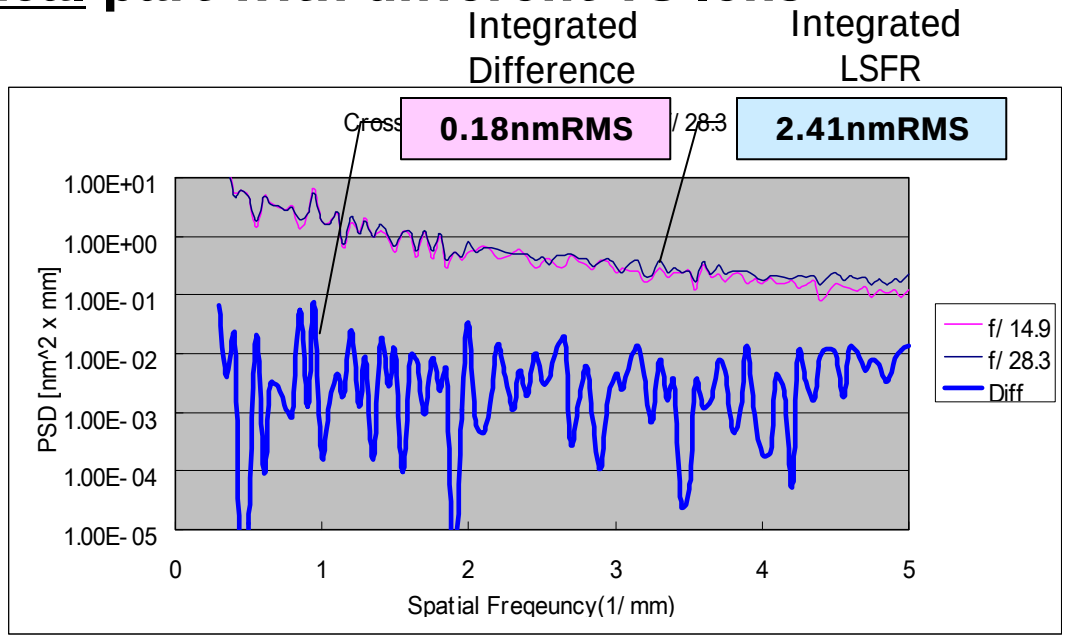
From “Advanced Metrology Tools Applied for Lithography Optics Fabrication and Testing” by Masaru Ohtsuka, *Production Engineering Research Laboratory , Canon Inc., OF&T 2006, Invited Paper* OFWC1, *OSA.*

Performance of MFA-400

(d)Cross test of aspherical part with different TS lens







-Same aspheric part is evaluated with different TS lenses (f/14.9 and f/28.3 converger) and compared as a cross test
-Both f/14.9 and f/28.3 are the stitched measurements
-Both TS reference surface are calibrated by modified random averaging method

Cross test difference is 0.18nmRMS(Target:0.2) for steep asphere

From "Advanced Metrology Tools Applied for Lithography Optics Fabrication and Testing" by Masaru Ohtsuka, *Production Engineering Research Laboratory , Canon Inc., OF&T 2006, Invited Paper* OFWC1, *OSA.*

Conclusion

- Demanding applications require high resolution metrology.
- An interferometer's true resolution are limited by the CCD, ITF, and bias sources (reference wave, retrace, etc).
- QED's Sub-aperture Stitching Interferometry products are able to stretch the ITF (while preserving low frequency data), and automatically calibrated systematic errors.
- The MFA 400 is an extremely high precision stitching interferometer designed specifically for measuring mid-spatial frequency errors on aspheres.

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