Developments in Sub-Aperture Techniques for Precision Mirror Fabrication

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Mirror Development
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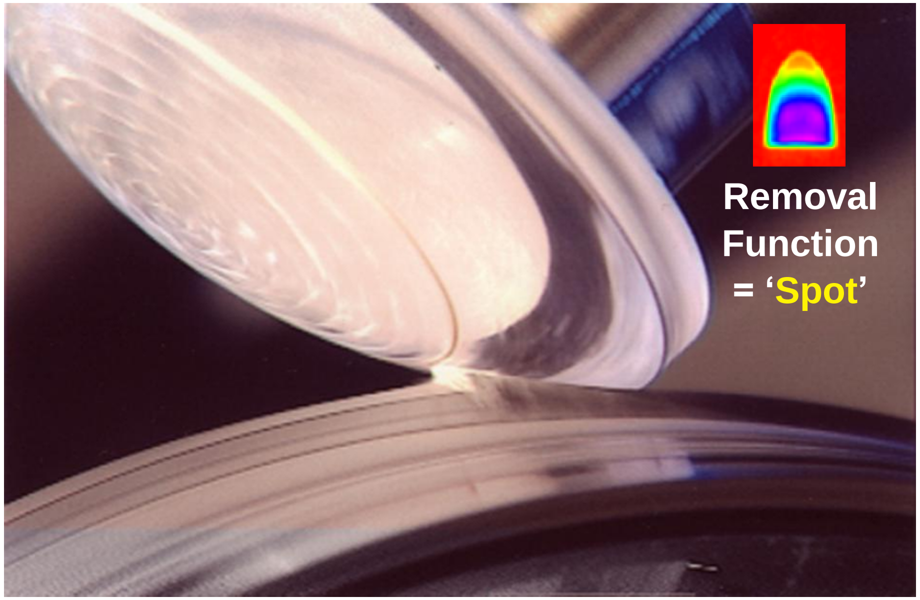
John West, John Hraba
Dr. Philip Stahl - NASA MSFC
Scott Antonille – NASA GSFC

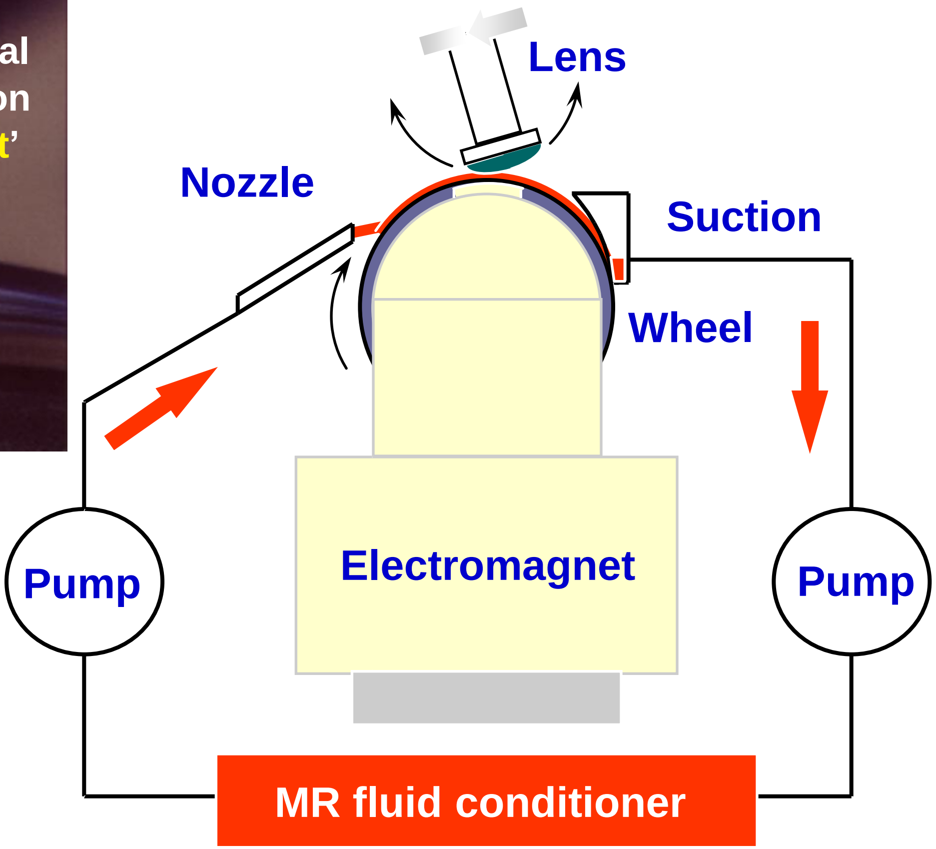
Outline

- **Brief MRF® technology introduction**
- **Demonstration of performance of 2-meter MRF platform**
- **Increase in aspheric departure that can be measured with Sub-Aperture Stitching Interferometry (SSI_A®)**

Magnetorheological Finishing (MRF) – How it works



MRF conforms to the workpiece surface



MRF – Breakthrough Technology

The MRF polishing tool:

- never dulls or changes
- is interferometrically characterized
- is easily adjusted
- conforms to part shape - works on complex shapes (flat, sphere, asphere, cylinder, freeform…)
- has high removal rates
- removal based on shear stress so applies very low normal load on abrasive, improving surface integrity
- determinism leads to high convergence rate

These attributes lead to a production-oriented, deterministic, computer-controlled polishing and figuring technique.

Production proven: more than 100 machines worldwide

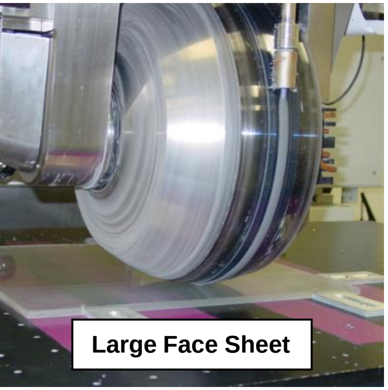
Polishing optics from 1mm to >1 meter

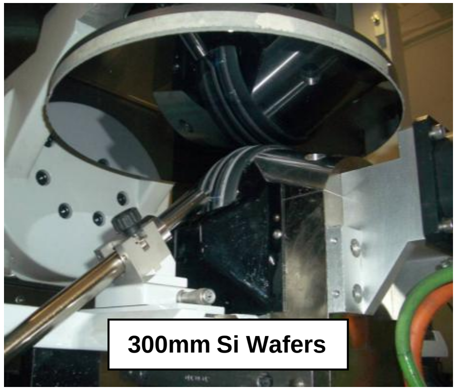
Family of QED Machines

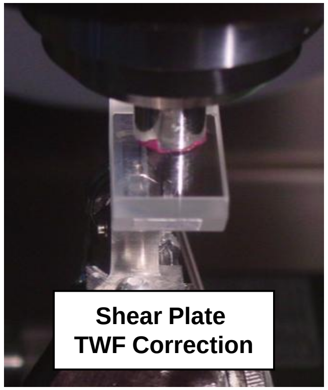
- **Q22-XE – <100 mm in diameter.**
- **Q22-X - Up to 200 mm in diameter.**
- **Q22-Y - Raster tool path, up to 200 mm in size.**
- **Q22-400X - Up to 400 mm in diameter.**
- **Q22-750P2 - Plano optics up to 750 mm x 1,000 mm in size.**
- **Q22-950F-Polishing Center– Freeform optics up to 950 x 1,250mm with pre-polishing capabilities**
- **Q22-2000F– Freeform optics up to 2+ meters**

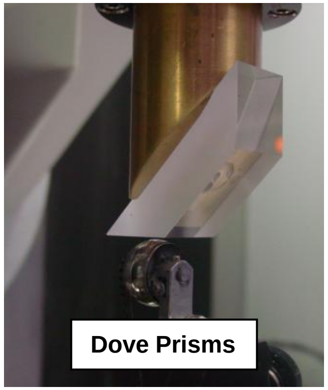
- **SSI® -- Subaperture Stitching Interferometer (SSI) for high precision metrology.**
- **SSI-A® -- Subaperture Stitching Interferometer (SSI) for high precision asphere metrology.**

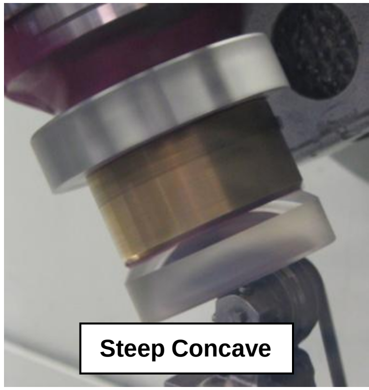
Range of MRF Applications

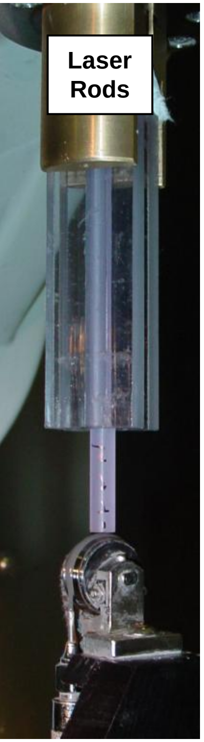

Large Face Sheet


300mm Si Wafers

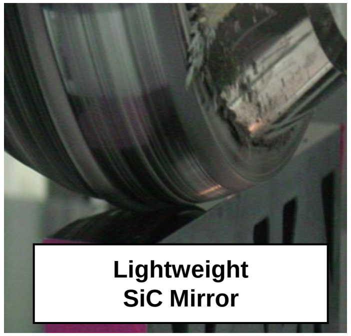

Shear Plate TWF Correction

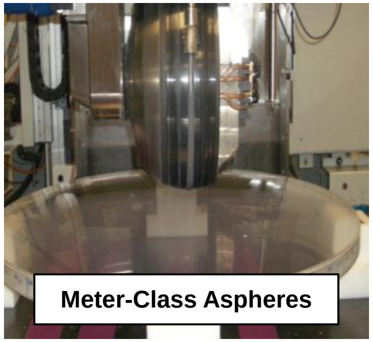

Dove Prisms

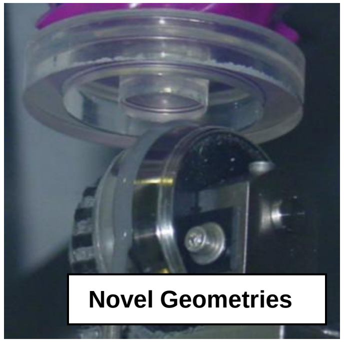

Steep Concave


Laser Rods


Lightweight Primary Mirror

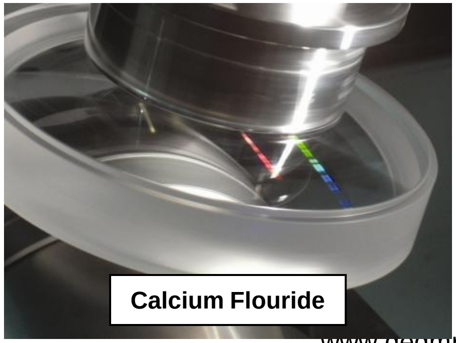

Lightweight SiC Mirror


Meter-Class Aspheres


Novel Geometries


Steep Aspheres

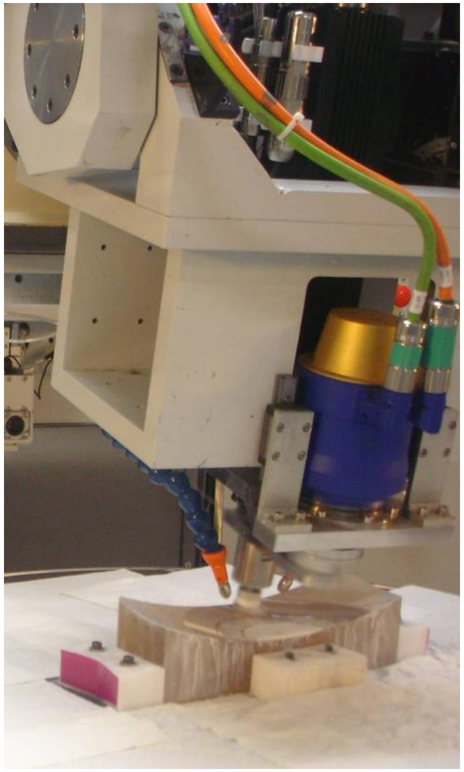

High Aspect Ratio Optics

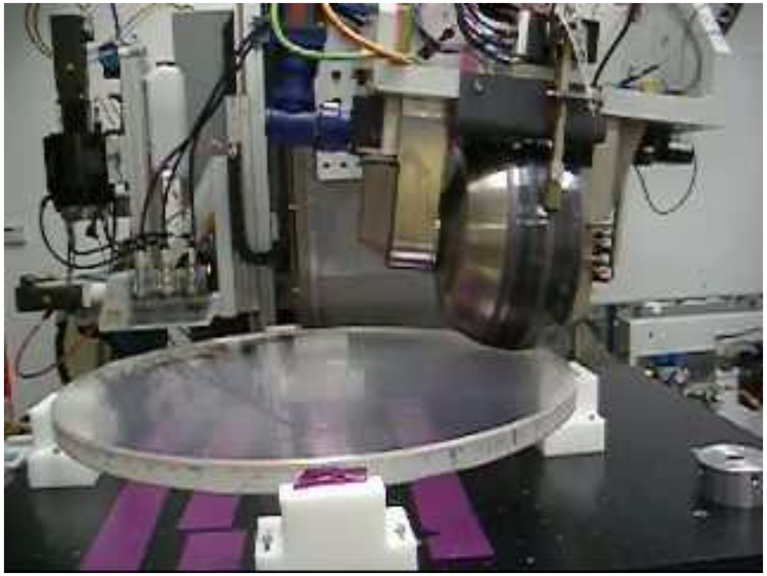

Calcium Flouride


Sapphire Windows


Off-axis Zerodur Component

Q22-950F





- Q22-950F can be outfitted with pad polishing and MRF
- This allows the user to go from ground state to finished surface

Q22-2000F

- 2-Meter Platform

Figure Correction – Large Primary

Part Description

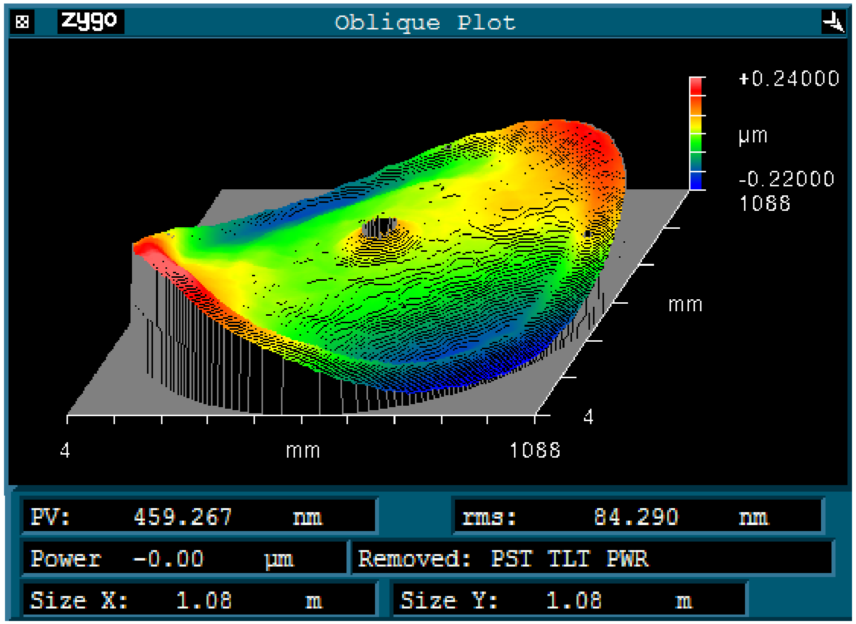
- QED has successfully delivered and installed an MRF machine capable of polishing 2-meter diameter optics
  - This machine is installed and has passed all acceptance test requirements

- Mirror Details
  - Outer Diameter: ~1.1 m (~43”)
  - Inner Diameter: ~0.1 m (~4”)
  - Radius of Curvature: ~3 m (~120”)
  - Material: Low expansion material
- Metrology
  - Full aperture
  - Standard surface reflection test

Figure Correction – Large Primary

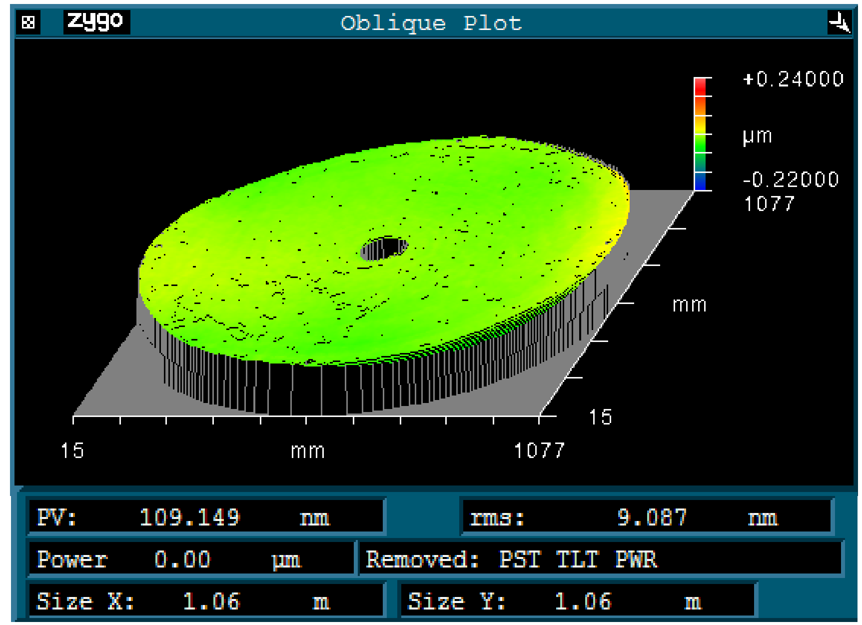
Global Figure over CA

Initial



RMS = 84 nm (~λ/7)

Final



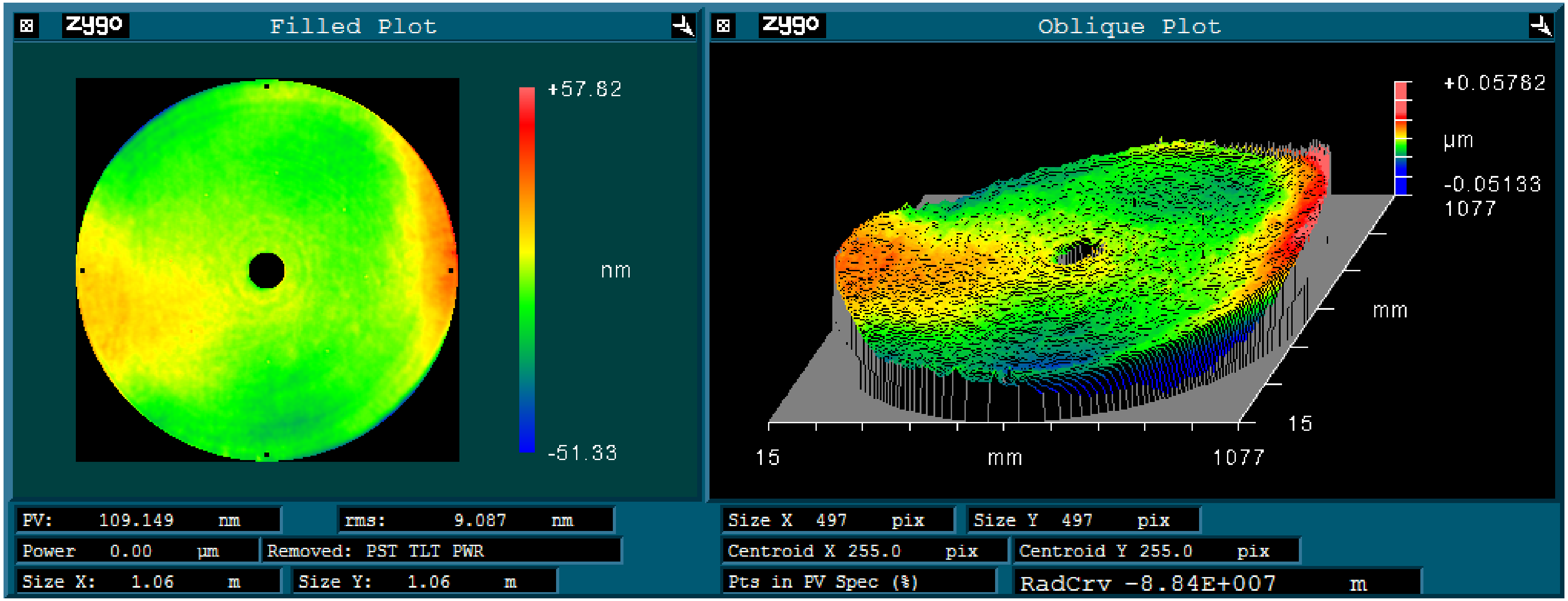
RMS = 9 nm (~λ/70)

- Only ***20 hours*** of polishing time
- Only ***2 iterations*** of MRF

***Fast Convergence* on Meter-Class Optics!**

Figure Correction – Large Primary

Close Look at Final Quality

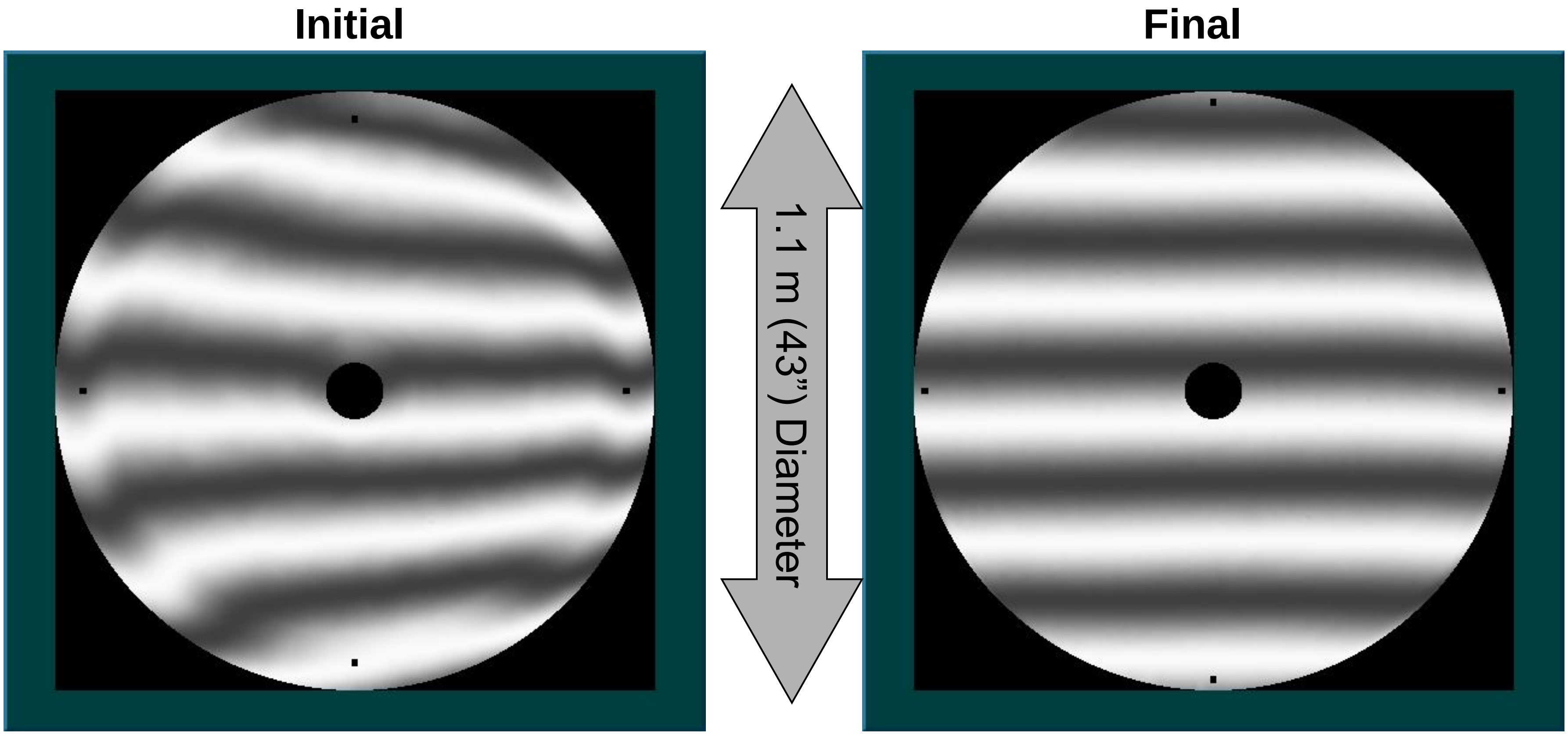


RMS = 9 nm (~λ/70)

- Metrology repeatability was limiting factor (due to time constraints)
- Much of residual astigmatism due to mounting distortions
- Could correct even further with improved metrology

Figure Correction – Large Primary

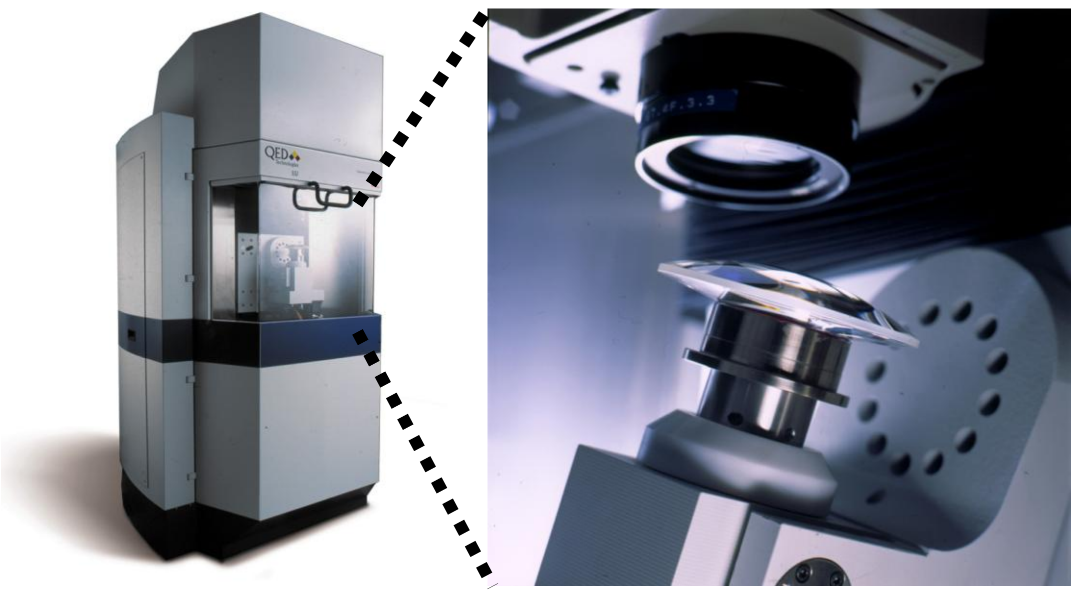
Synthetic Fringes Before & After



- **2 MRF Iterations: 14 hrs + 6 hrs = 20 hours total**
- **Overnight, unattended operation**
- **Fast, deterministic convergence on meter-class mirrors!**

Subaperture Stitching Interferometer (SSI®)

- Precision six axis machine
- Standard Zygo® 4” or 6” interferometer
- QED control software: automation + advanced algorithms



SSI advantages

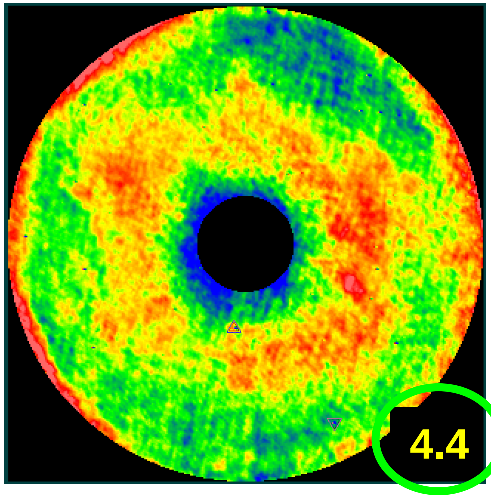
- Cost-effective measurement of larger apertures
- Automatic, inline calibration of systematic error
- Increased lateral resolution
- Measures mild aspheres *without dedicated nulls*!

SSI-A® example

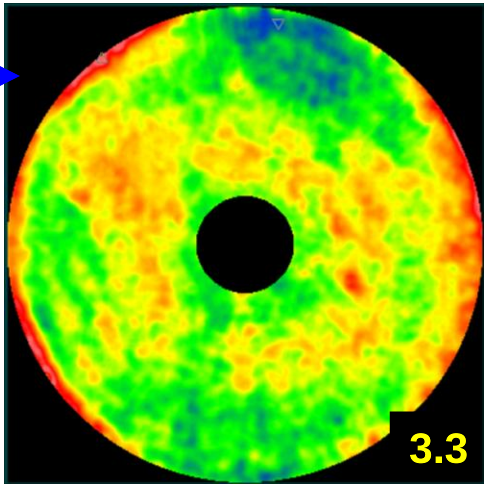
Cabot Microelectronics

- R –226 mm; CA 100 mm; ~25 λ from b.f.s.
- Secondary mirror for the PICTURE / SHARPI programs
- Good agreement with vendor's null test
  - But again, note the finer structure resolved

Stitch map



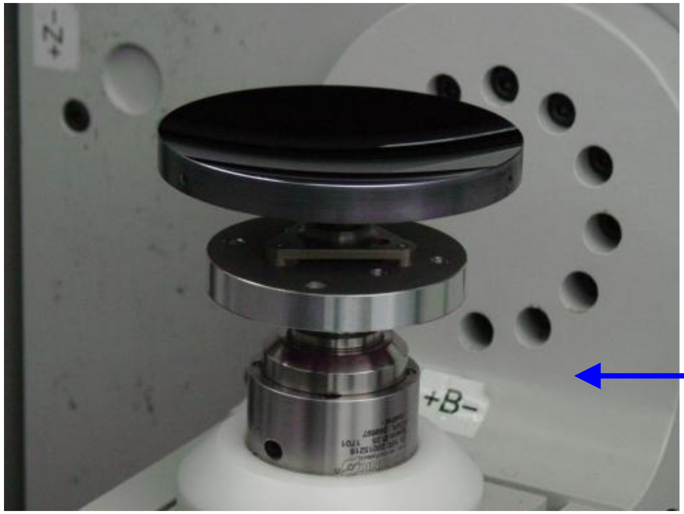
Conic null test



Null test data courtesy of Jay Schwartz, L3-SSG-Tinsley

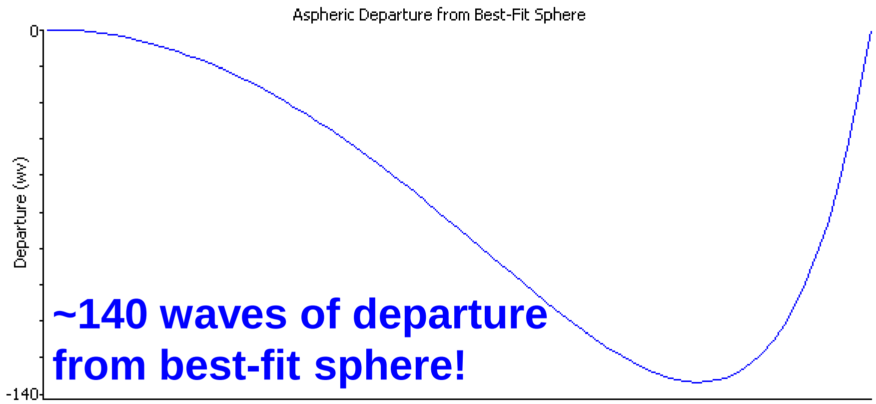
Scale +/- 12.5 nm

Test part courtesy of Scott Antonille, NASA Goddard

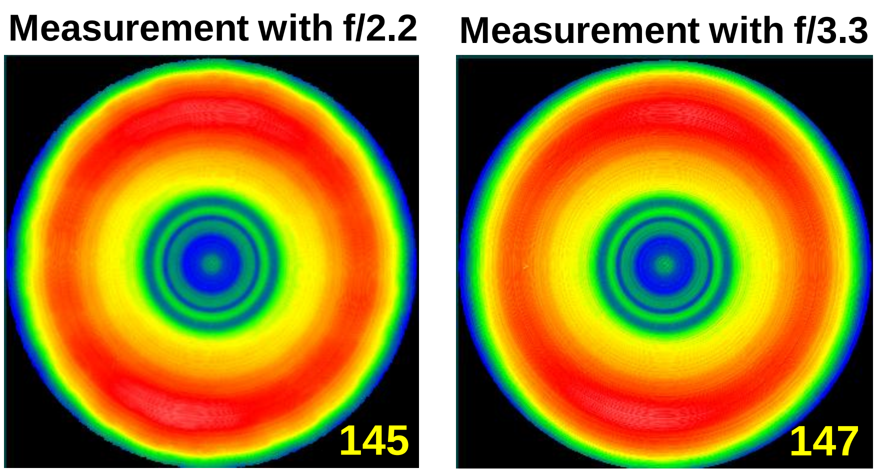


New SSI-A software release!

- More aspheric capability
  - Up to ~200 waves from best-fit sphere *without dedicated null lenses*
  - Aperture converter and small Transmission Spheres enable more radii and R/#s
- Enhanced usability
  - Consolidated advanced options reduces confusion
  - SSI setup wizards simplify configuring the SSI
  - and other conveniences!

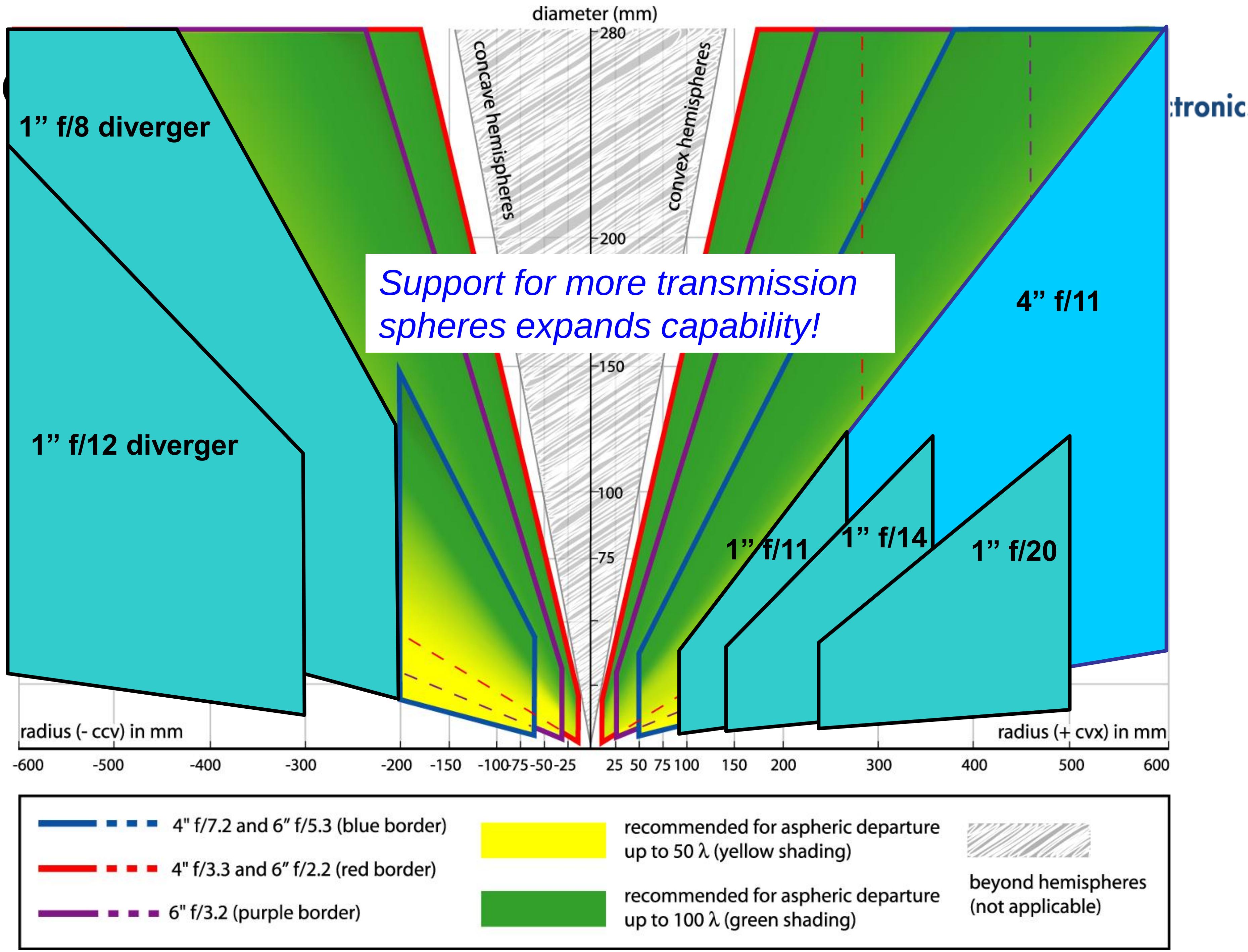


Excellent measurement reproducibility



Aperture converter and small transmission spheres

- Software enables use of aperture converters and small TSs
  - Higher magnification; more aspheric departure possible
  - Enables more parts to fit within the SSI 1 meter-long envelope



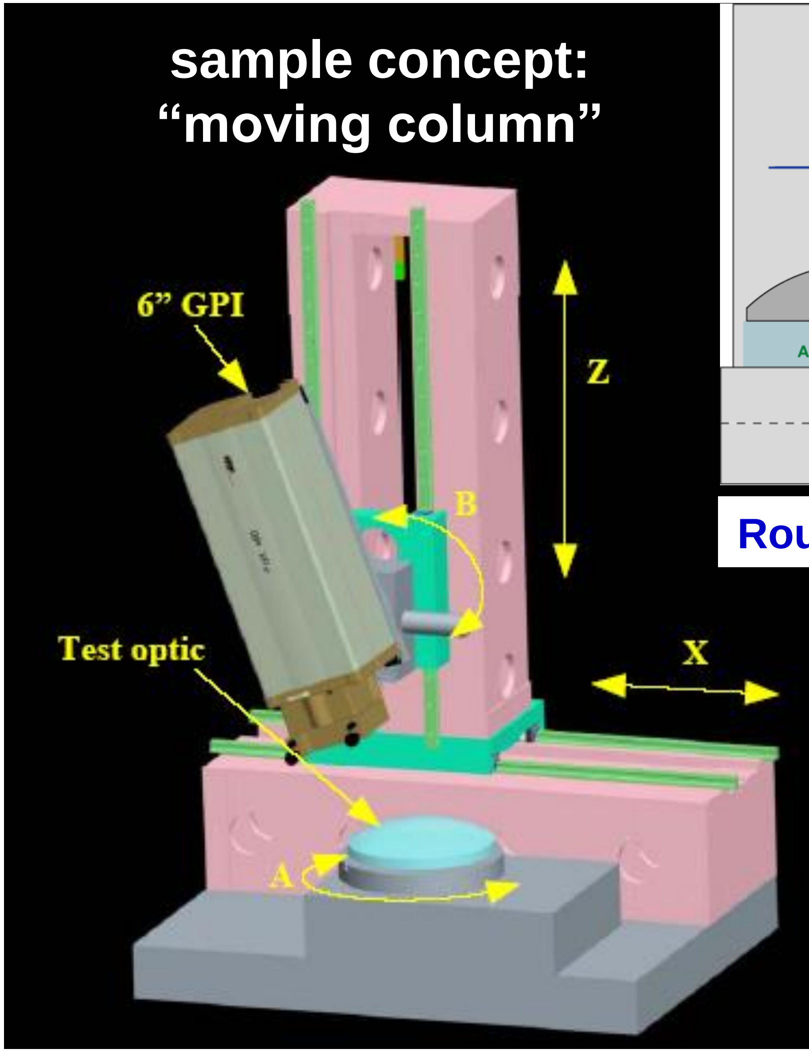
diameter (mm)
280
200
150
100
75
concave hemispheres
convex hemispheres
1" f/8 diverger
1" f/12 diverger
Support for more transmission spheres expands capability!
4" f/11
1" f/11
1" f/14
1" f/20
radius (- ccv) in mm
radius (+ cvx) in mm
-600 -500 -400 -300 -200 -150 -100 -75 -50 -25 25 50 75 100 150 200 300 400 500 600
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)

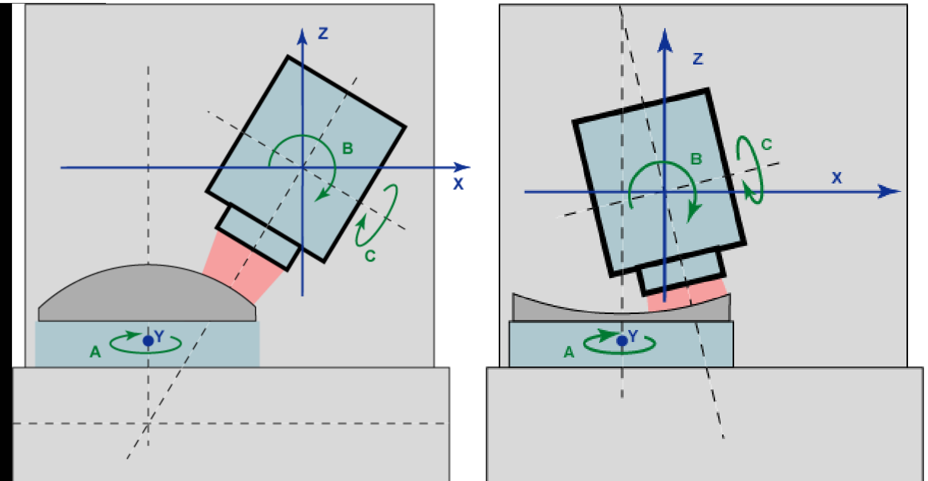
Larger optics: scaling the SSI®

- Benefits specific to large optics
  - Avoid fabrication of huge transmission spheres and null optics for convex surfaces (e.g. secondary mirrors)
  - No dedicated nulls (and painful calibration of them) for mild to moderate aspheric departures
  - Reduced cavity lengths (and air turbulence) for concave optics (via use of diverging TSs)
  - Improved spatial resolution (for edges and MSFs)

- Scaling up involves significant hardware changes
  - Increased size, larger X travel; tilt the interferometer, not the part
    - Need to avoid the greater mechanical distortions for large parts
  - Interferometer size selection has some trade-offs
    - 6” mainframe: lower cost (especially for TSs), easier to move
    - Cycle times and possible accuracy trade-offs
      - (e.g. for a 1.5 m segment, 6”:~400 subapertures; 12”: ~100)

Larger platform concept





Rough schematics of tilting interferometer

Stitching technology is scalable to larger optics in both vertical and horizontal configurations.

Summary

- Unique attributes of MRF give it the flexibility for polishing complex shapes to high precision with excellent convergence rates
- QED continues to extend the aperture size that can be finished and recently installed and demonstrated performance of a 2-meter freeform platform
  - Precision finishing of a mirror > 1 meter in size was demonstrated – 2 iteration, 20 hours of polishing
  - Very fast convergence and short cycle times demonstrated on meter-class optics
- Increased aspheric departure can now be measured using stitching interferometry (SSI_A) - ~200 waves of departure
- Stitching interferometry can be scaled to address meter class optics
- QED remains committed to delivering state-of-the-art solutions for optics fabrication challenges

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