Status of Sub-Aperture Finishing and Metrology Development

presented to:
Mirror Technology SBIR/STTR Workshop
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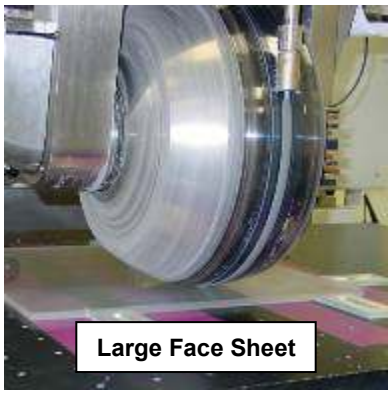
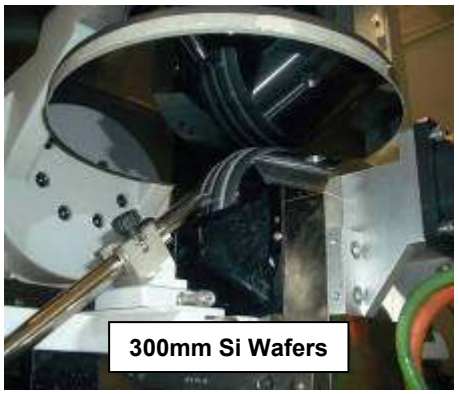
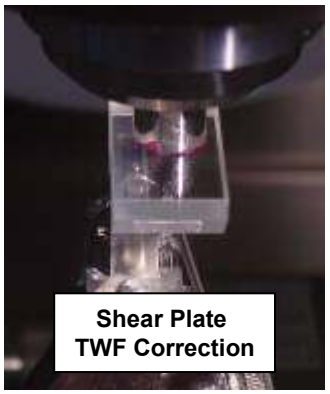
Acknowledgements:

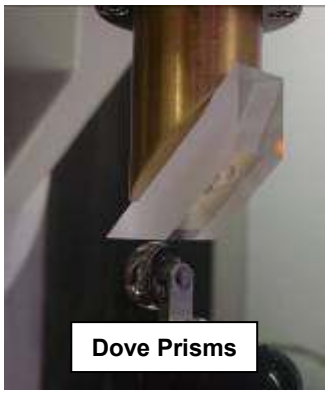
NASA: John West, John Hraba, Phil Stahl, Scott Antonille + many DoD sponsors

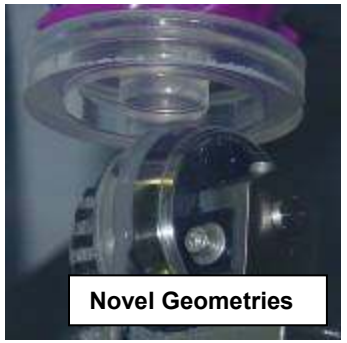
Range of MRF Applications

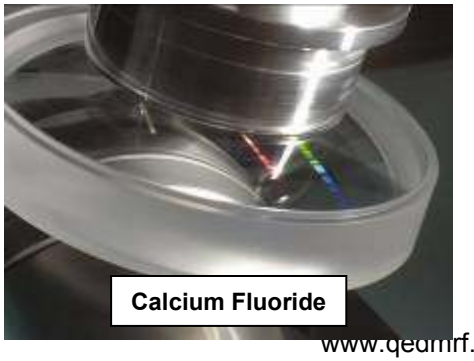




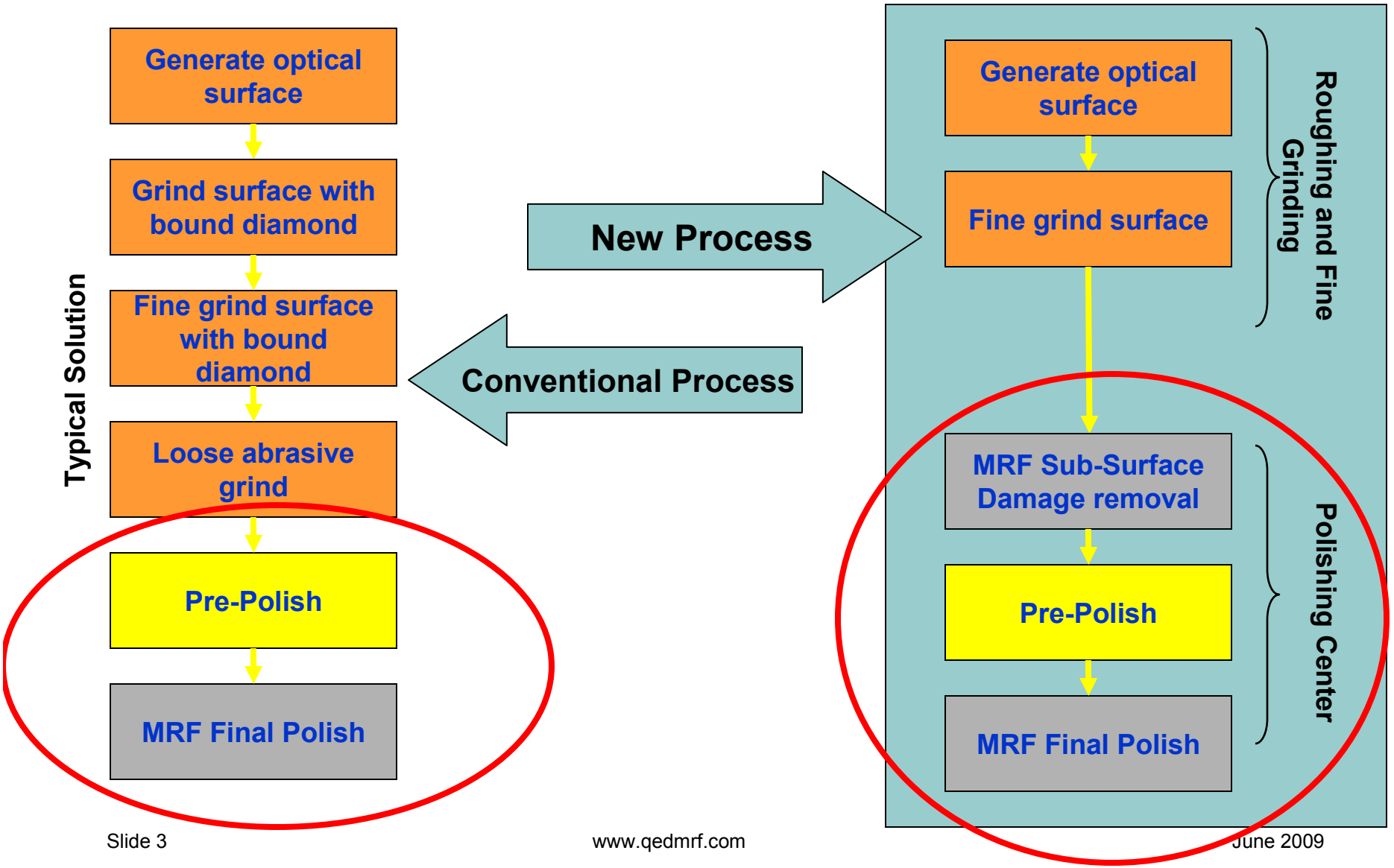






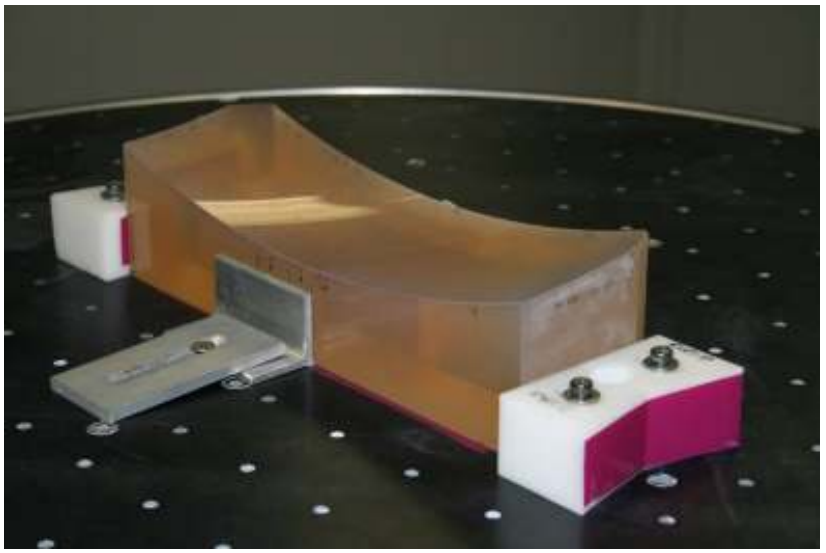


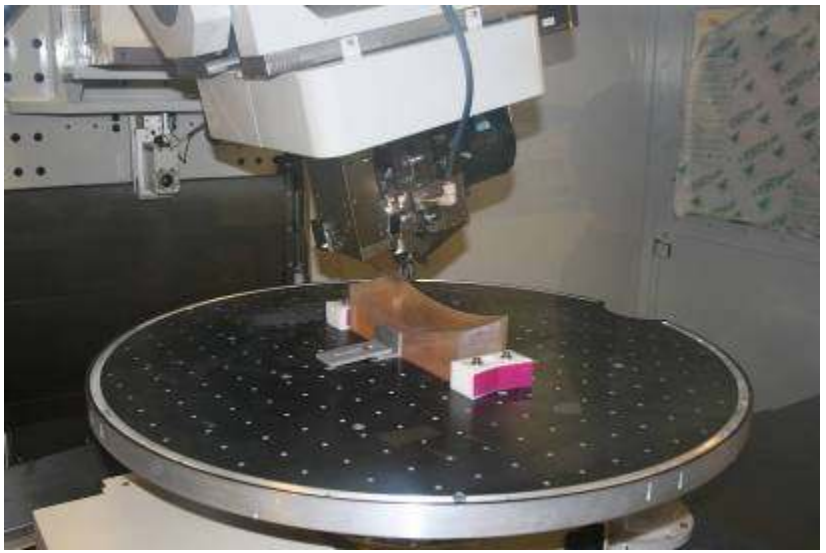
Novel Process Flow

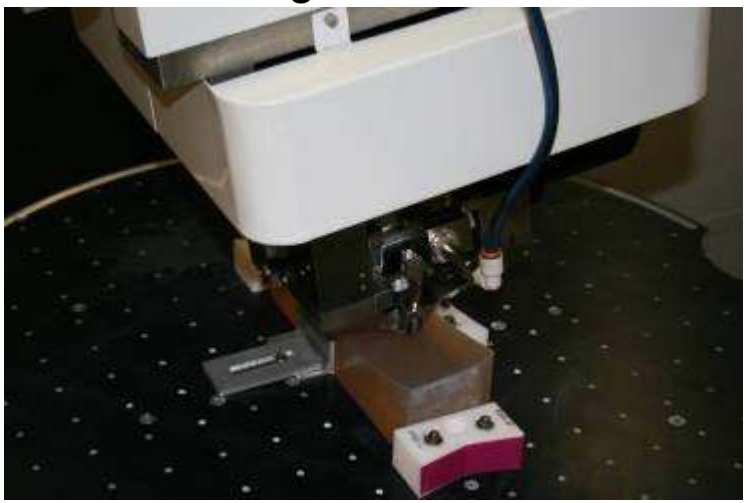


Example: off-axis component

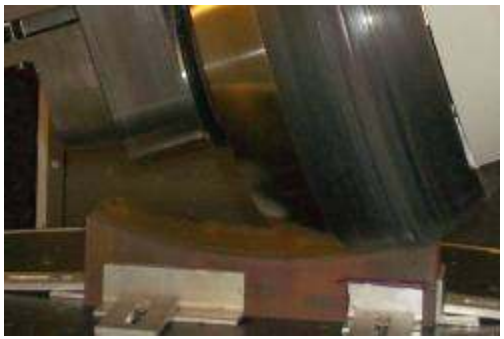
- ~300 x 90 mm off-axis spherical section
- ~286 x 72 mm Clear Aperture
- R = - 450 mm (cc)
- Zerodur
- Process on Q22-950 PC
  - MRF Damage Removal ~ 6 um
  - Smoothing (sub-ap pitch tool) ~ 6 um
  - MRF Figure Correction ~ 4 um





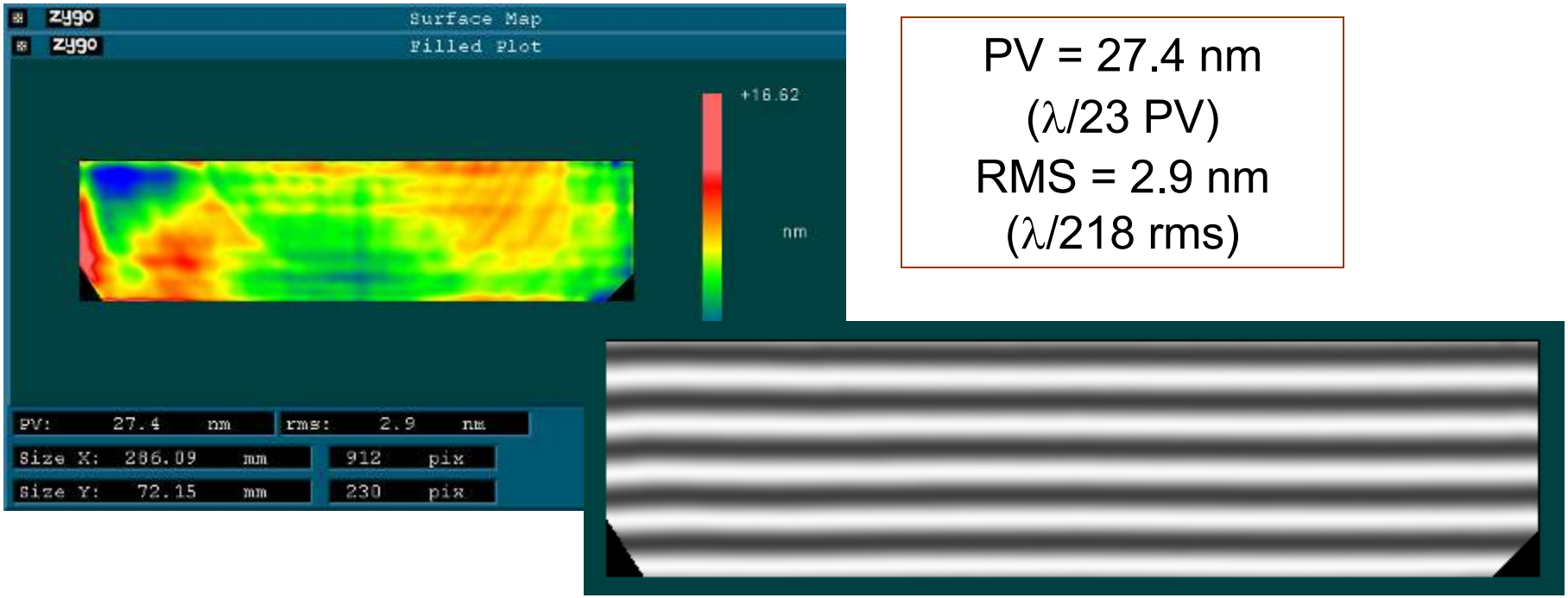


Actual Part



- **After an initial (process development part), a second, identical part was processed from the ground state**
- **This demonstrated a stable repeatable process**
- **Initial: 4.0 μm PV, 0.7 μm rms**

Final Measurement - (Only Piston, Tilt & Power Removed)



PV = 27.4 nm
(λ/23 PV)
RMS = 2.9 nm
(λ/218 rms)

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-A®:** mild aspheres metrology without null lenses
- **ASI™:** high-departure aspheres metrology

Q22-2000F MRF® Polishing Center

- Optics up to 2.4 m in diameter
- Round, Rectangular, Hexagonal apertures
- Plano, sphere, asphere, freeform
- Precise figuring
- Fast convergence

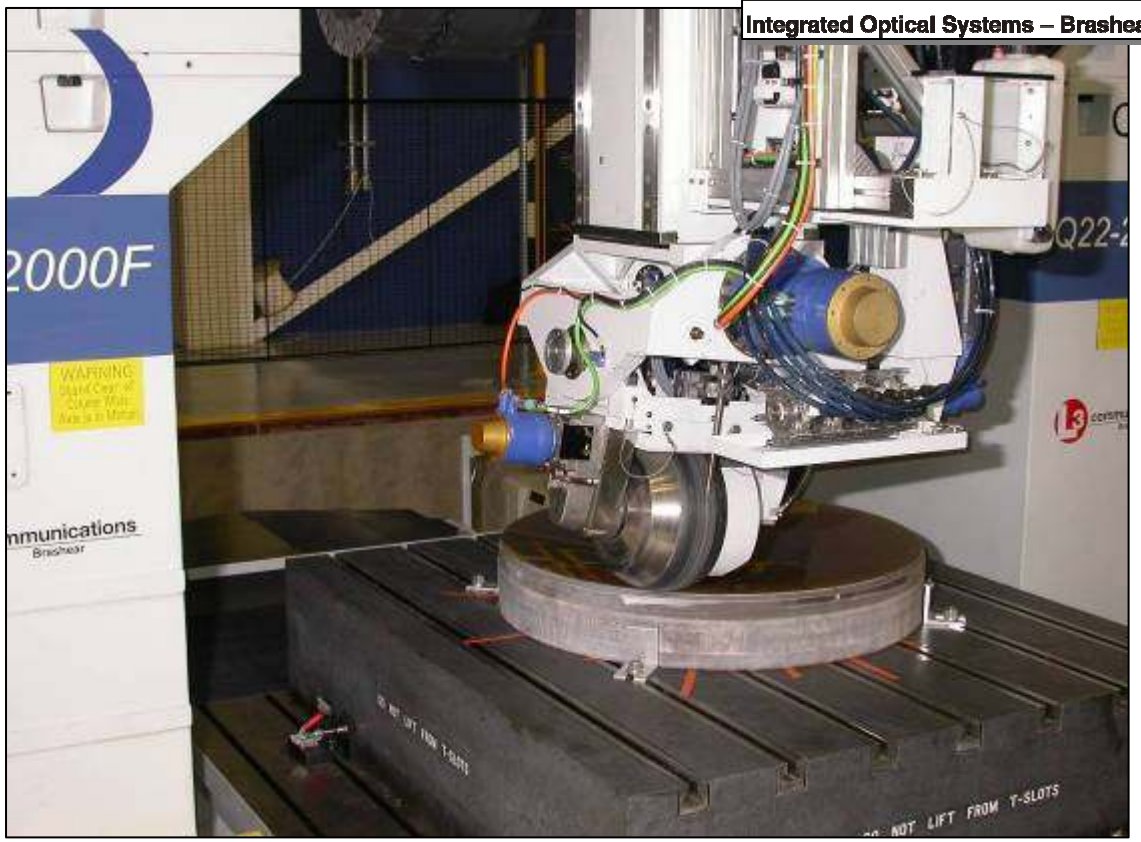
Q22-2000F MRF Polishing Center at Brashear

Integrated Optical Systems – Brashear

Q22-2000F in action

Polishing meter(s) class optics

- 1.1-m diameter
- R = 3-m concave sphere
- Material: Cervit
- C10+ fluid (cerium-oxide based)
- Center of curvature interferometric test
- Starting figure error was 84 nm RMS
- Only two MRF single scan runs to completion!



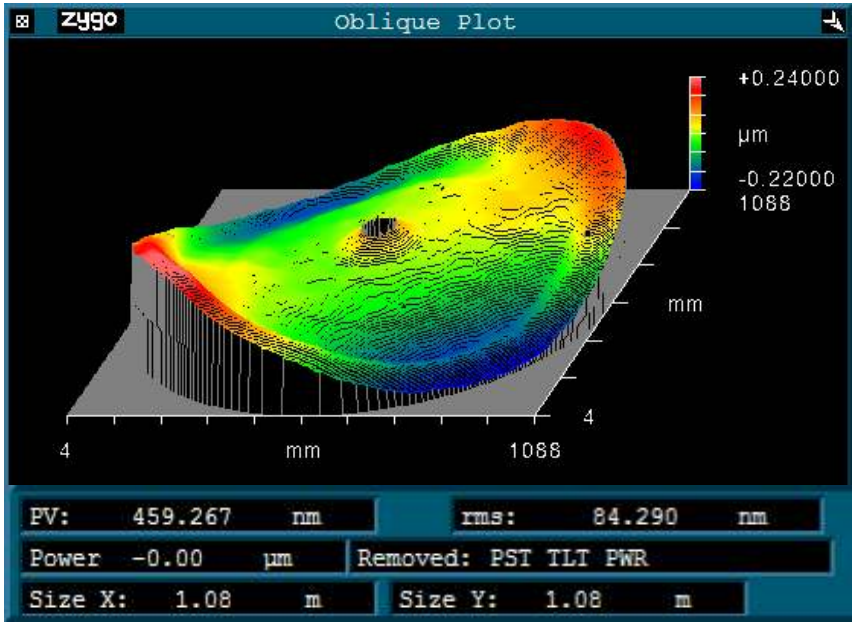
Data courtesy of L-3 IOS Brashear Optics,
615 Epsilon Drive, Pittsburgh, PA 15238, USA

Reference: F. Piché, A. Clarkson, W. Messner, C. Supranowitz, P. Dumas, "Precision figure correction of two-meter optics with magnetorheological finishing (MRF)", Optifab 2009, Proceedings of SPIE Vol. TD06-49, May 2009.

Figure Correction: Large Primary

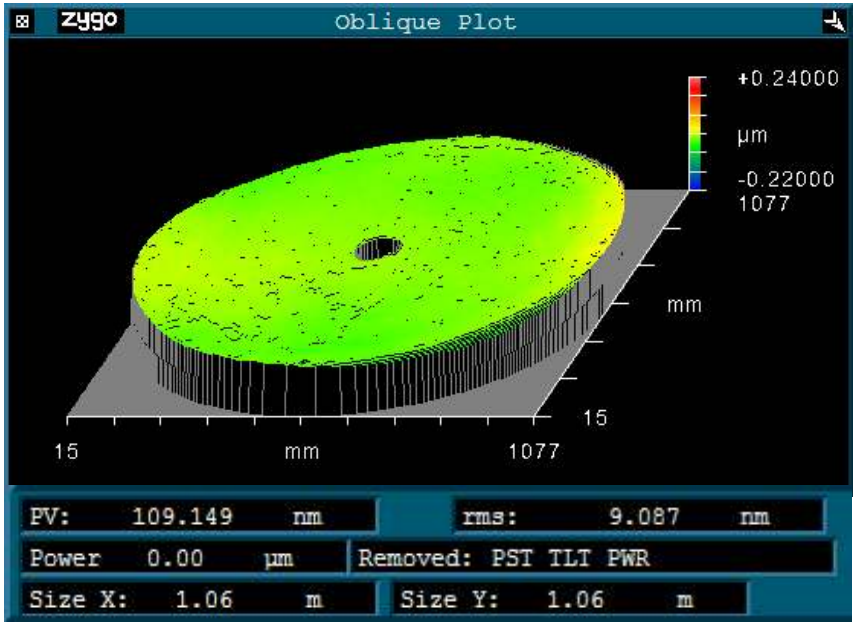
Global Figure over Clear Aperture (CA)

Initial



RMS = 84 nm (~λ/7)

Final



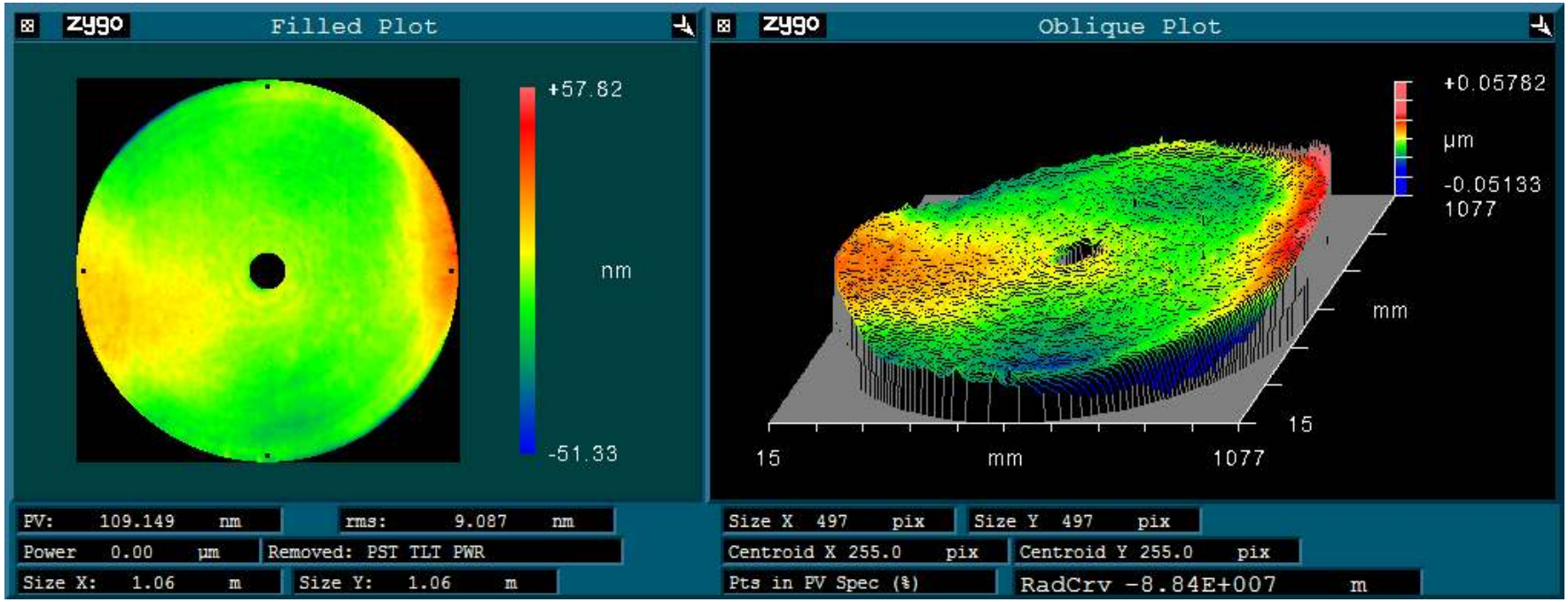
RMS = 9 nm (~λ/70)

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

<u>Fast Convergence</u> on Meter-Class Optics!

Figure Correction: Large Primary

Close Look at Final Quality

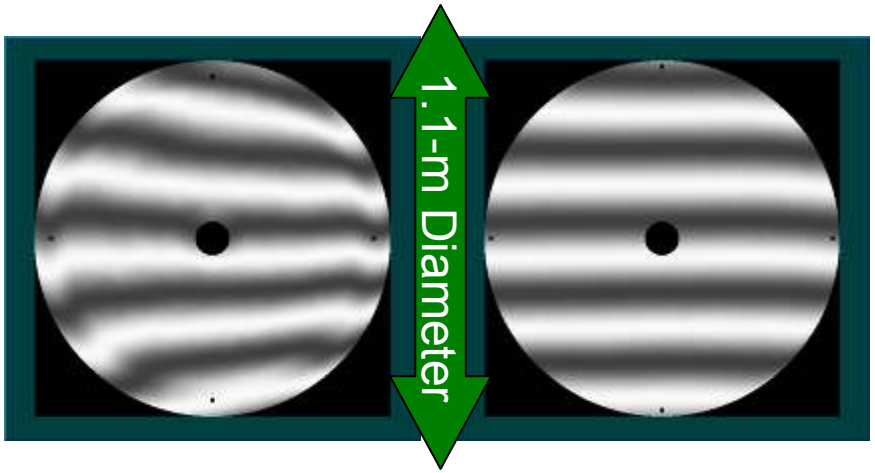


RMS = 9 nm (~λ/70)

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

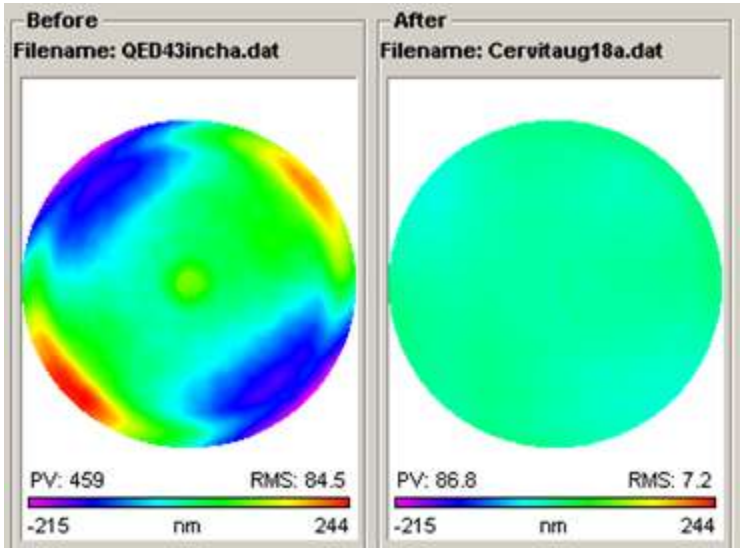
Q22-2000F in action

Polishing meter(s) class optics



Synthetic Fringes of Initial & Final Phase Map

20 hours total MRF Polishing - 2 Iterations



MRF convergence rate: 70+ %

- Calculate convergence by ratio of measurement metric: after RMS figure/before RMS figure
- First run: 14 hours
  - 84.5 nm RMS → 20.2 nm RMS
  - 76% convergence rate
- Second run: 6 hours
  - 20.2 nm RMS → 7.2 nm RMS
  - 64% convergence rate (limited by metrology capability)

L3 Integrated Optical Systems – Brashear

Data courtesy of L-3 IOS Brashear Optics

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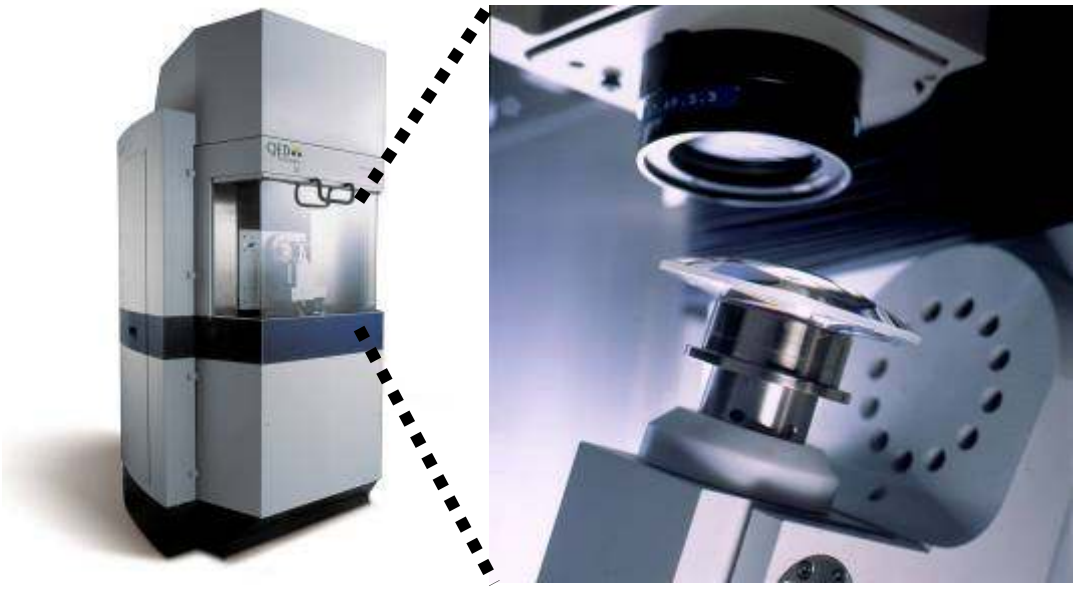
- **ASI™:** high-departure aspheres metrology

Subaperture Stitching Interferometry (SSI®)

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

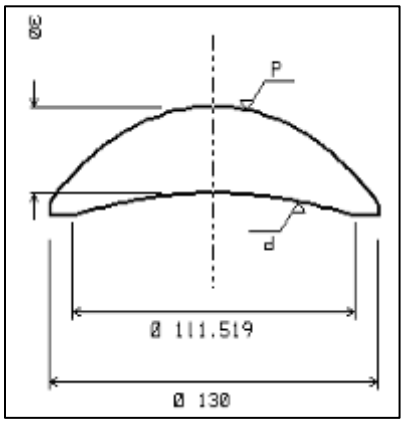


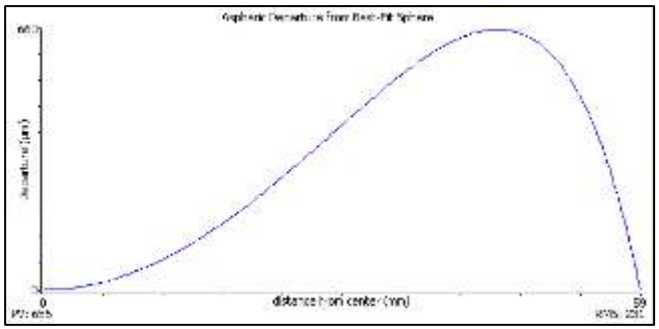
SSI advantages

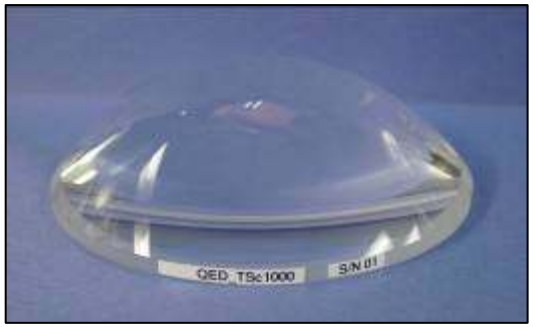
- **Cost-effective measurement of larger apertures**
- **Automatic, inline calibration of systematic error**
- **Increased lateral resolution**
- **SSIa to measures mild aspheres *without dedicated nulls*!**

Example: 1000 Wave Asphere

- 118 mm CA
- 72 mm vertex radius
- 656 micron departure from best fit sphere
- High NA and aspheric departure make this asphere difficult to measure with other techniques

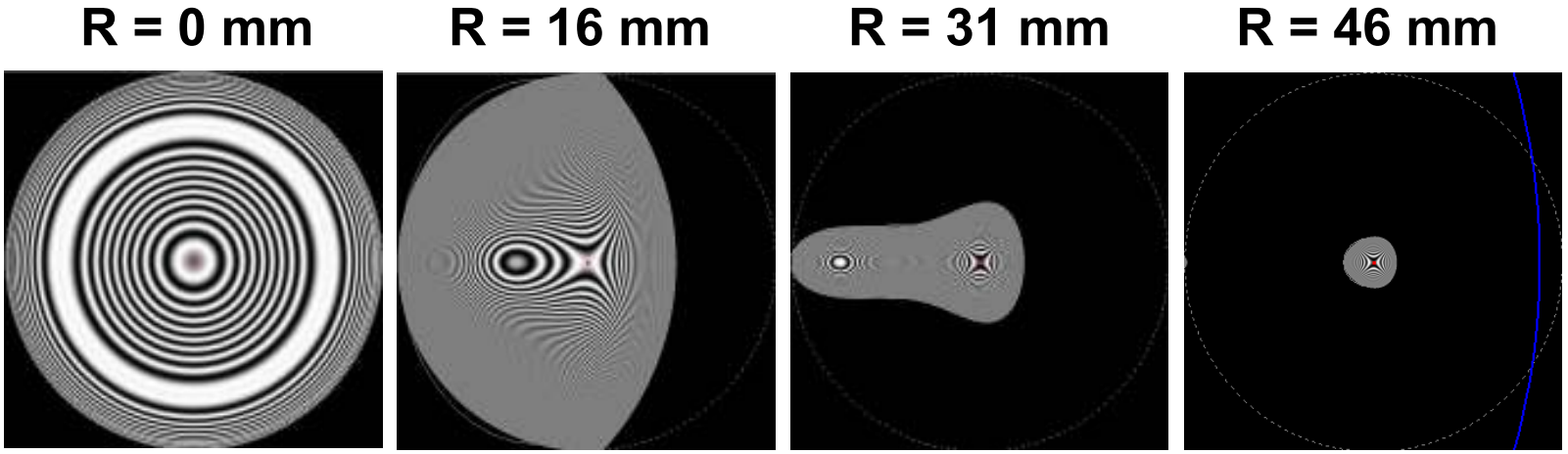


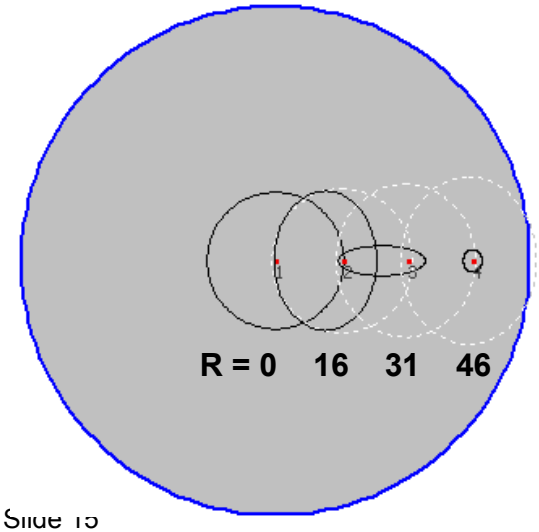




Increasing Aspheric Departure

As the aspheric departure increases…

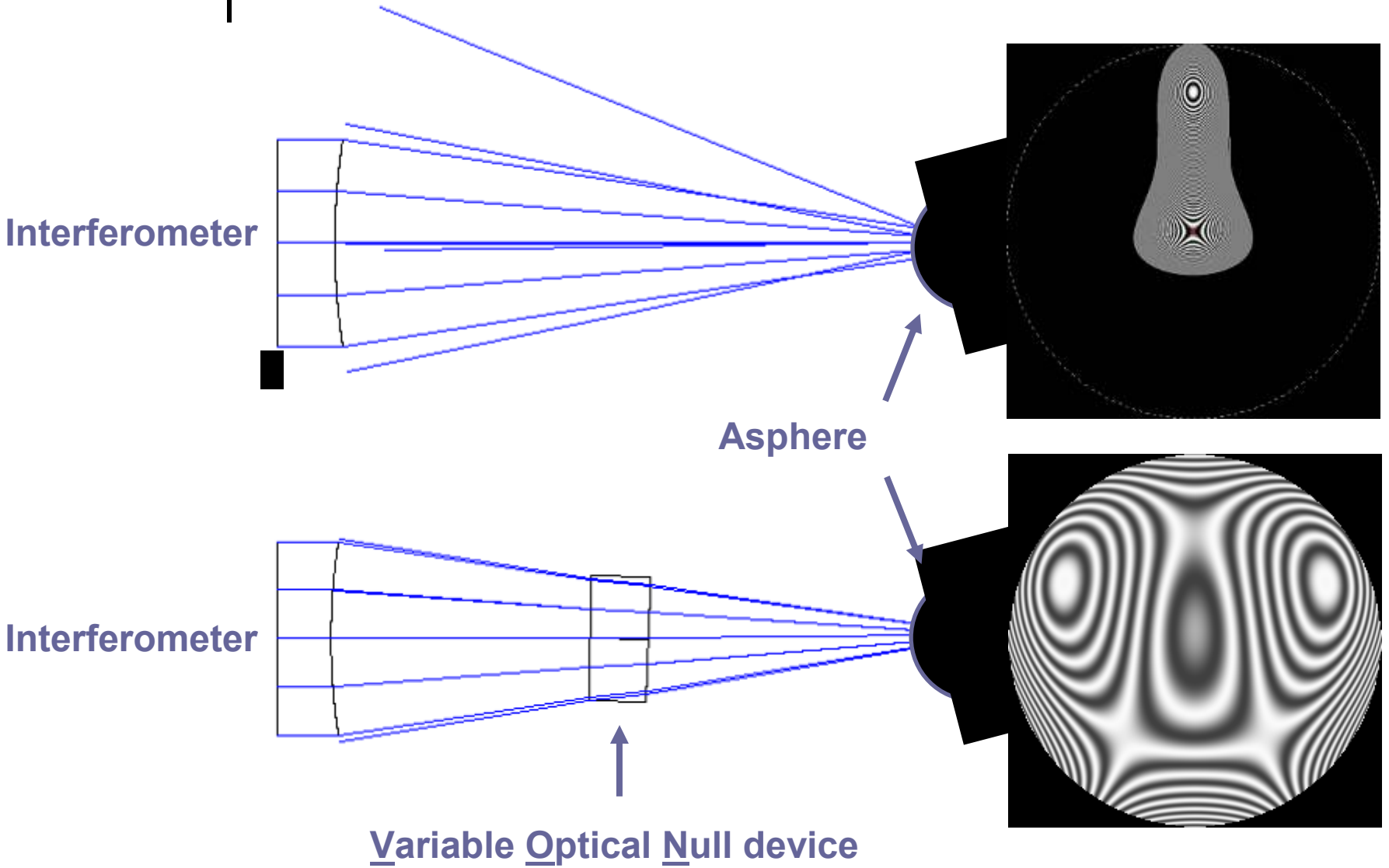




The increasing fringe density causes data dropouts within the sub-aperture, resulting in…

more sub-apertures required to cover the surface, and longer measurement times.

Variable Optical Null (VON™) Device



Requirements for a VON

- Configurable, to measure many aspheres
  - Needs only to match local shape of asphere within a subaperture
  - For most aspheres, this consists of low-order aberrations (astigmatism, coma, trefoil)
  - Ability to vary relative amounts of each aberration
- Use simple optics/mechanics
  - Easy to make, align, calibrate
  - Simple model for wavefront generated

Our Particular VON

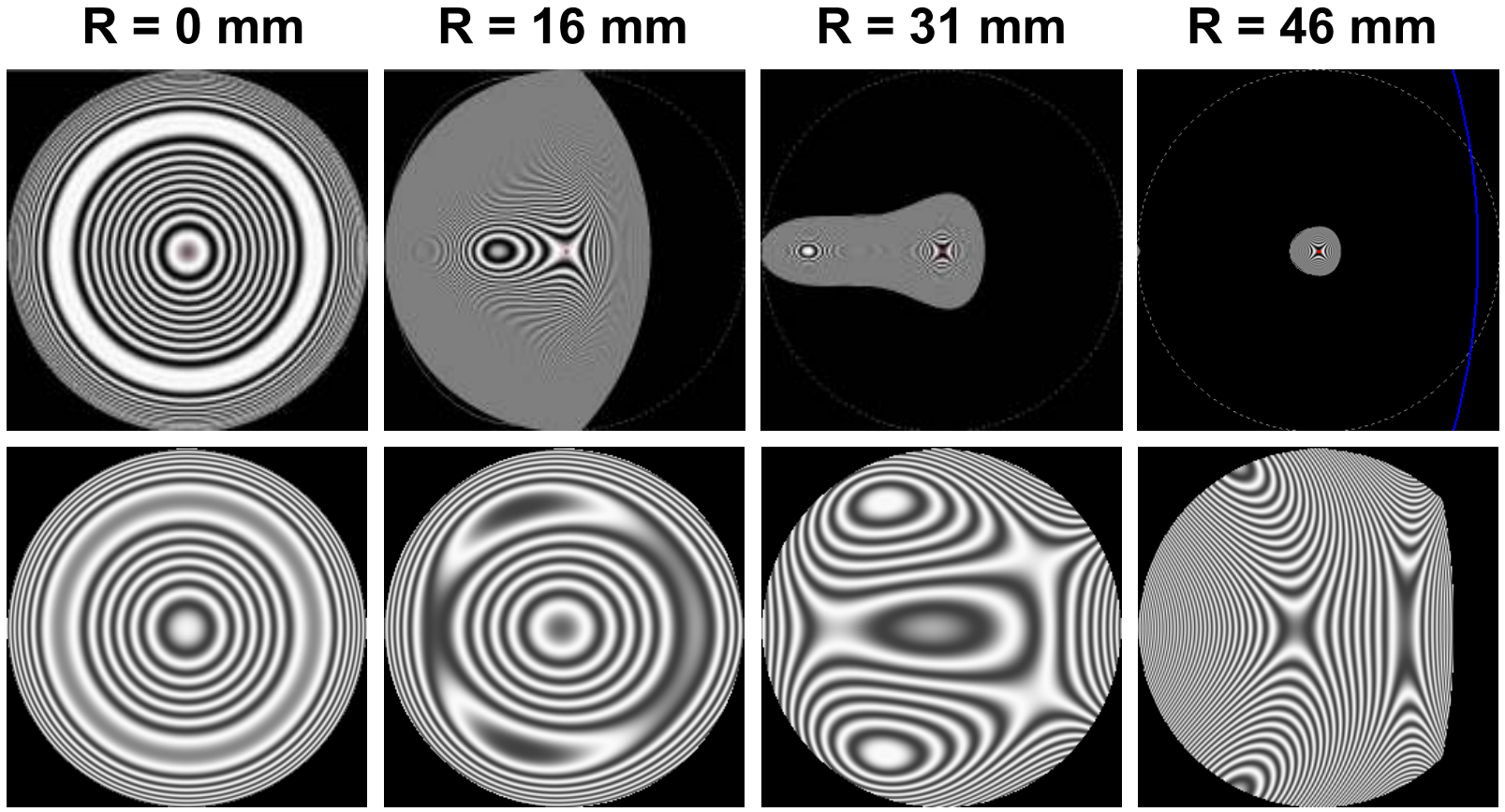
- Counter-rotating optical wedges

Plane-parallel

Maximum wedge

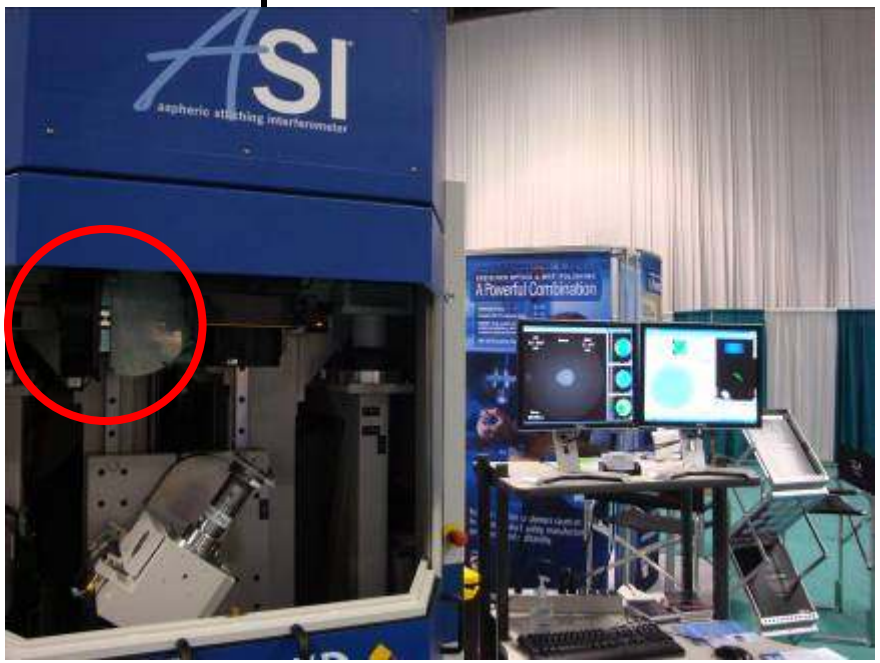
- By varying the total wedge angle and tilt, the VON produces low-order aberrations:
  - Astigmatism, coma, trefoil
- Flat surfaces only, simple mechanical motions

Variable Optical Null (VON) Device



- Only need to match the low-order aberrations of each subaperture, producing resolvable fringes over entire field
- Combine measurement of residuals with nominal wavefront of VON

ASI in action during Optifab
Sub-aps with or without VON

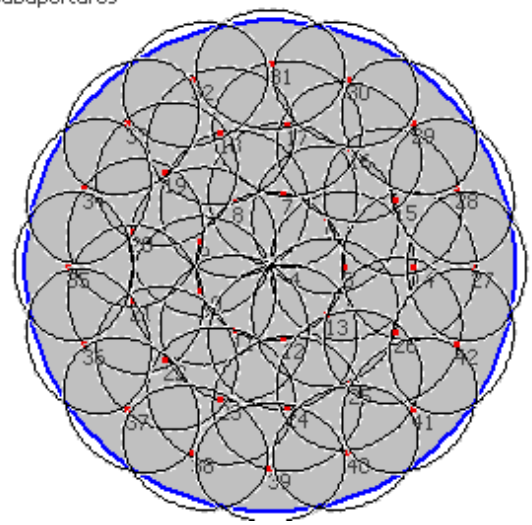


Without VON

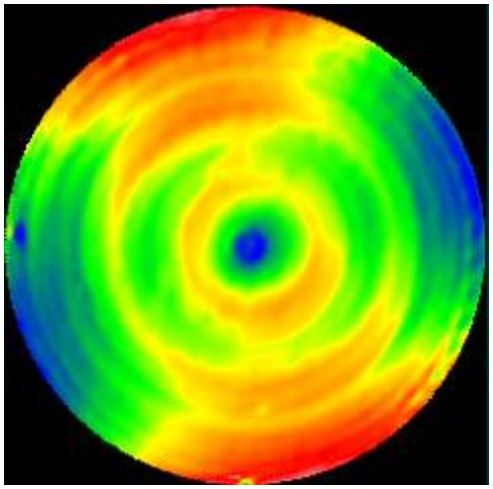
With VON

(Early) Measurement Results

42 Subapertures

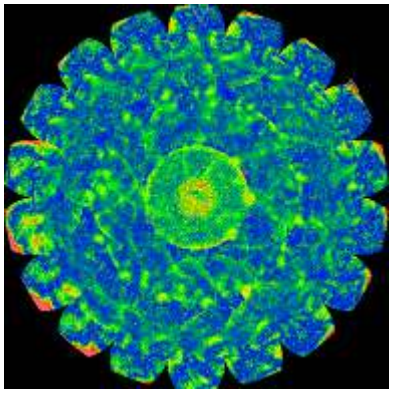


Measurement Lattice



rms = 147nm

- Measurement result using 6” F/2.2 transmission sphere
- ~40 subapertures
- ~15 minute measurement time
- Low mismatch error (3.6nm)



Mismatch map: rms = 3.6nm

ASI™ Summary

- The use of configurable null optics with subaperture stitching allows for:
  - Large aspheric departure measurement capability (up to 1000λ)
  - Shorter measurement times (fewer sub-apertures)

- While maintaining all of the original benefits of subaperture stitching interferometry:
  - Full aperture coverage
  - Higher lateral resolution
  - Increased accuracy
  - Aspheric measurements without dedicated nulls

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