Status of Sub-Aperture Finishing and Metrology Development

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NASA: John West, John Hraba, Phil Stahl, Scott Antonille + many DoD sponsors
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 Fluoride
- Sapphire Windows
- Off-axis Zerodur Component
Novel Process Flow

Typical Solution

- Generate optical surface
- Grind surface with bound diamond
- Fine grind surface with bound diamond
- Loose abrasive grind
- Pre-Polish
- MRF Final Polish

New Process

- Generate optical surface
- Fine grind surface
- MRF Sub-Surface Damage removal
- Pre-Polish
- MRF Final Polish

Conventional Process

- Generate optical surface
- Fine grind surface
- MRF Sub-Surface Damage removal
- Pre-Polish
- MRF Final Polish

Roughing and Fine Grinding

Polishing Center
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
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 ($\lambda/23$ PV)
RMS = 2.9 nm ($\lambda/218$ 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
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

Figure Correction: Large Primary
Global Figure over Clear Aperture (CA)

Initial
• Only 20 hours of polishing time
• Only 2 iterations of MRF

```
Initial:
PV: 459.267 mm
rms: 84.290 mm
Power: -0.00 μm
Size X: 1.08 m
Size Y: 1.08 m
```

Final
```
Final:
PV: 109.149 mm
rms: 9.087 mm
Power: 0.00 μm
Size X: 1.06 m
Size Y: 1.06 m
```

RMS = 84 nm (~λ/7)  
RMS = 9 nm (~λ/70)

Fast Convergence on Meter-Class Optics!
Figure Correction: Large Primary

Close Look at Final Quality

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

RMS = 9 nm (~λ/70)
Q22-2000F in action
Polishing meter(s) class optics

Synthetic Fringes of Initial & Final Phase Map
20 hours total MRF Polishing - 2 Iterations

- 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)

MRF convergence rate: 70+ %

Data courtesy of L-3 IOS Brashear Optics
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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

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 1000\(\lambda\))
  - 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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