Case Study – Next generation ground based telescopes

- E-ELT Primary - 906 segments each 1.45m wide
- TMT Primary – 492 segments each 1.44m wide
- Significant manufacturing challenge
- Challenges conventional paradigms
Optics Manufacturing Requirements

- Speed/Cost
  - Sub-surface damage
  - Material removal rates
  - Determinism/Convergence
- Mid-Spatial frequencies
- Scalability
  - Large clear aperture
  - Smaller feature sizes
Our Programs

<table>
<thead>
<tr>
<th>Year</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>Process results on flats, SSD Studies (MDA Phase 1, NASA Phase 1, ARL)</td>
</tr>
<tr>
<td>2006</td>
<td>Mild on-axis aspheres (MDA Phase 1, ARL)</td>
</tr>
<tr>
<td>2007</td>
<td>Extension to large apertures (NASA Phase 2, ARL, U.S. Government)</td>
</tr>
<tr>
<td>2008</td>
<td>Extension to fast off-axis aspheres (MDA Phase 2, ARL)</td>
</tr>
</tbody>
</table>

- **W911NF-04-2-0001** – Army Research Laboratory  
  COTR: Dr. Jane Adams
- **NNM06AA11C** – NASA Phase 2 SBIR – MSFC  
  COTR: Mr. John West
- **W9113M-07-C-0149** – MDA Phase 2 SBIR – AFRL  
  COTR: Dr. Larry Matson
- **NNX08CC82P** – NASA Phase 1 SBIR – MSFC  
  COTR: Mr. William Jones
- **U.S. Government Contract**
To look ahead, Look back

- 2001 - Lab demonstration
- 2004 – Prototype machines (350mm)
- 2005 – Shipment of prototype to Cranfield, Swing Arm Profilometry
- 2006 – First asphere figuring
- 2007 – Moving torch design, 1.2m tool design Production of aspheres
- 2008 – Prototype machines (350mm)
2007/2008 RAPT Optics Roadmap

- Release of EOS 500
- Integration of Helios with other platforms
- Ability to imprint high-frequency features
- Shipment of Helios 1200 tool to Cranfield
- Off-axis metrology, production of off-axis segments
- Gimbaled torch

8/26/2008 NASA Mirror Tech days
The Chemistry of the Process

\[ \text{Rate} = Ae^{-\frac{E_a}{RT}} \]

For SiO\(_2\):
\[ \text{SiO}_2 + \text{CF}_4 \rightarrow \text{SiF}_4 + \text{CO}_2 \]

For silicon:
\[ \text{Si} + \text{CF}_4 + \text{O}_2 \rightarrow \text{SiF}_4 + \text{CO}_2 \]

For SiC:
\[ \text{SiC} + \text{CF}_4 + \text{O}_2 \rightarrow \text{SiF}_4 + 2\text{CO} \]

- Reaction Products Must be Volatile
- Other plasmas - other materials e.g. Ni, Be, Ti...

- Damage-free figuring @ atmospheric pressure
- Gaussian footprint for chemical figuring tool
  - Arrhenius rate reaction
Torch Technology Roadmap
Figuring capability as a function of spatial frequency

- Gaussian does not introduce ringing but is limited in ability to figure higher spatial frequencies
- Roadmap to changing spot size on the fly to permit MRR vs. figuring capability tradeoff
RAP IMP – Application to SiC

- High activation energy for SiC – thermal management during figuring critical
- Considerable knowhow to minimize edge-effects
- Polycrystalline/multi-phase materials roughen up, iteration between figuring and buffing needed to obtain desired figure/roughness
- 150\textsuperscript{th} wave RMS figure and 3 Angstroms RMS roughness achieved repeatably
RAP Assisted Manufacturing

- Material Removal Rate
- SSD removal/figuring
- Determinism
  - Repeatability
  - Uniformity of neutral removal
  - Figuring capability ($f(\omega_s)$)
- Roughness Evolution
  - Grain boundaries
  - Sub-surface damage sites
  - Inclusions and inhomogeneity
- Manufacturing economy
Fused Silica (3 um removal)

- 2-5 Angstroms roughness increase
- 3 runs @ 750 nm each
- 5 m/min scan speeds
RAP Figuring

Tool Influence Function

RAP process conditions:
Estimated run time: 12 mins/run
Number of iterations: 2

Cross-sectional profiles

Pre RAP
Post-RAP I
Post-RAP II

Distance (cm)
Height (waves)

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Roughness Measurements – NewView @ 20X

Pre-RAP

Post-RAP

1.5\lambda of material removed

Pre-RAP

Post-RAP

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Tool Path Algorithm

- Decouple path planning from dwell algorithm
- Dwell algorithm accepts
  - Error map
  - Footprint
  - PER
- Outputs
  - ROC
  - Dwell map
- Path planning based on machine configuration/options
NASA SBIR Phase II
~100% Clear Aperture

- 6” Clear Aperture
- Light-weighted SiC primary
- f/4 Parabola
  - Pathfinder to a 12” CA, f/2 Parabola
  - Meter class segmented mirror pathfinder
Motion platform
MDA Phase II: 5-Axis Upgrade, 300mm RAP Tool

- 2 Axis Tip Tilt Torch Stage
  - Built on 300 mm Proto 1 Platform
  - Increased Z Stroke: 100mm travel
  - Working Travel: +/- 30 degrees
  - Max Angular Velocity: 44 deg/sec
  - Integrated IR Heater Assembly
  - Additional Electrical Enclosure required for 2X servo amplifiers
  - Lightweight Torch and Matching Network

8/26/2008

NASA Mirror Tech days
MDA Phase II: Primary Mirror Substrate

- Off-axis ellipse
- f/0.76
- Poco Graphite Material
NASA ConX [IXO] – SBIR Phase I

- “Fabricate & Assemble” approach
- Slumped glass mirrors with glass spacers (wedges)
  - Curvature
  - Thickness taper in optical axis
  - Radial thickness
- Phase 1 demonstrator
  - 10 μm wedges on 1mm thick, 100mm square flats
  - Borosilicate glass
  - Metrology challenge (warp)
  - NewView slices (subtractive maps)
NASA ConX [IXO] – SBIR Phase I

- Met program objectives
- Rapid manufacturing of wedges is possible
- Extend to curved surfaces
- Metrology challenges
Helios range of tools

- Astronomy applications
- Helios 1200 is the first offering
  - Cranfield University is our first customer
  - Machine commissioned at Cranfield University
- Configurable in various platforms per user specification
- Simplified CNC motion control
  - G codes
  - PVT specifications
Machine Pictures
Patterning Capability

- Patterning ULE posts
- 10 μm tall
- Range of diameters
  - 450 μm to 850 μm
500mm Tool – EOS Series

- Standard offering
  - 5 axis tool
- 500mm clear aperture
- Tip tilt to handle upto f/0.3 surfaces
- Available for sale in Dec. 2008
- Torch design allows easy integration onto other motion control platforms
- Roadmap to smaller footprints
Conclusions

• Rapid manufacturing using a combination of conventional and non-conventional steps

• Utilize RAP for damage-free shaping, damage removal, and/or final figuring *where appropriate*

• Non-contact, Atmospheric pressure operation

• Rapid optics fabrication leads to
  – big reductions in schedule risk
  – quicker prototyping/design cycles
  – lower overall program cost/performance risk

• Scaling
  – Larger clear apertures
  – Smaller features (on the fly)
Questions?