4-m NWO Telescope Design

Steve Kendrick
Ball Aerospace & Technologies Corp.
Overview of Optical Systems Engineering for 4-m aperture NWO telescope

- Systems Engineering for large (4-m) aperture telescope
  - Based on Mission Requirements

- Primary Mirror options
  - Monolithic or Segmented (non-deployed)
  - Mirror Stiffness Approach
  - Control Systems – actuators, wavefront sensing

- Mirror optical fabrication approaches
  - Examples of fabrication techniques and potential vendors

- Optical coating fabrication candidates

- Summary
NWO Telescope Design Approach is Based on Mission Requirements

- Design for large aperture observatory based on science requirements
- Derived architecture approach to fulfill science mission

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NWO Telescope Design
Future Trades for Primary Mirror

- Segmentation and construction options

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<td>Semi-rigid mirror</td>
<td>Dozens of actuators</td>
<td>6-DOF plus curvature</td>
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<td>100s to 1000s of actuators</td>
<td>Dozens of actuators per segment</td>
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- The necessary trades include:
  - Mirror stiffness (including materials)
  - Geometry
  - Alignment compatibility
  - Optical performance
  - Surface control
  - Manufacturability
Manufacturing issues affecting cost, complexity, and performance

- **ULE® and Zerodur®**
  - Both capable of 4 m monolith
  - Some differences in manufacturing and lightweighting techniques

- **Silicon Carbide (SiC)**
  - Lack of heritage for achieving visible-light quality
  - Domestic facilities up to about 1.8 to 2-m diameter

- **Optical Coating chamber limitations**
  - Only one domestic chamber identified that can coat larger than 3-m
Monolithic / Segmented PM Considerations

- **Science Impact**
  - Scatter, diffraction impact on signal-to-noise of discerning Earth-like planets around exosolar star

- **Engineering Impact**
  - Scatter and PSF requirements
  - PM and total telescope system mass
  - Control System
  - Error budgets on components, alignment

- **Manufacturability**
  - Schedule
  - Cost

Conclusions:
- Segmented mirror has slightly detrimental science impact relative to monolithic mirror
- Sensing and control makes segmented PM more complex, and in some ways more risky than a monolithic PM
- A 4-m monolithic NWO PM is feasible
  - can be fabricated from the blank through the coating phases
  - multiple vendors available for each major fabrication process
- Preliminary: monolithic is preferable up to 4-5 m diam
Science Impact —
Stray light from diffraction sidelobes

- In the starshade’s shadow, telescope faces $<10^{-8}$ of target star light
  - Diffraction sidelobes from obscurations and segmentation are acceptable
  - On-axis telescope system is desirable to reduce packaging constraints

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<th>Spider Type</th>
<th>Sidelobe Intensity</th>
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<td>4-leg</td>
<td>$(3.3\times10^{-4}) (\lambda/\mu m)^2 (\theta/\text{arcsec})^{-2}$</td>
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<td>$(8\times10^{-5}) (\lambda/\mu m)^2 (\theta/\text{arcsec})^{-2}$</td>
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- PM segment scatter from stars outside the telescope FOV

  Minimal segmentation with perfect wavefront gives 6-fold sidelobes with peak intensity $< (10^{-3}) (\lambda/\mu m)^2 (\theta/\text{arcsec})^{-2}$

  - Nearest mag 15 star (average ~70" away) gives mag 32 in planet pixel at worst possible orientation

- Effect of segment misalignments can be large at large angles
Engineering impacts

- Mass is driven by required mirror stiffness and gravity sag during tests
  - For a given stiffness, segments have lower areal density than monolithic PM
  - Must include actuator mass and backplanes appropriate for each mirror type

- Stiffness requirements can be very different
  - Rigid PM must verify it will be correctly figured passively on orbit
  - Semirigid/Flexible/Segmented PM must verify it can be aligned to correct figure on orbit

- Mirror polishing specifications –
  - Segments require tighter rms surface quality to make room for new WFE budget terms

- Mirror prescription
  - Monolithic mirror would be on-axis
  - Segments would each be off-axis optics

Control System for segmented PM

- Assume PM comprises 6 segments
  - More segmentation requires more unique prescriptions and higher total costs

- At least 7 DOF actuation / segment
  - RoC actuator for fabrication variability
  - Hexapod for rigid body alignment
  - Future trade on higher number of actuators

- Requires a wavefront sensor
  - Baseline would be JWST-like phase retrieval approach
  - Visible-UV science wavelengths
    - Accuracy and bandwidth likely more demanding than JWST
  - Only need diffraction limited wavefront
    - Less demanding than internal-coronagraph TPF-C candidates,
Summary: Monolith/Segments

- Mirror costs dependent on mass, WFE, and segmentation parameters
- 4-m PM currently feasible as either monolithic or segmented
- Various cost approaches yield roughly even cost comparison for the two
- Recommend reviewing this trade in Phase A
  - Cost, risk, technology

Kahan & Targove (Proc SPIE 3356, 1998) estimated the breakpoint for a 7-segment vs. monolithic PM \( \sim 4\text{m} \)
For a 9-segment vs. monolithic PM \( \sim 5\text{m} \)
Manufacturability

Substrate Material – Zerodur and ULE blanks can be made at 4m size

Lightweighting – Can be performed on 4-m optics by several vendors

Polishing – Can be performed on 4-m optics by several vendors

Optical coating – One vendor identified in continental US for 4-m optics
Material Candidates

- **Material properties**
  - CTE, CTE homogeneity, thermal conductivity, density, stiffness, etc.
  - Thermal gradients expected but rotisserie effects can be avoided
  - Fabrication and test temperatures vs. operating temperature
  - Rigid vs. Semi-rigid vs. Membrane
  - Ease of lightweighting, imposing integral mounting interfaces, polishing

- **NWO material candidates**
  - ULE®, Zerodur® borosilicate, fused silica – all can be used for up to 4-m monoliths
    - Zerodur® 4-m blank(s) are sometimes in-stock at Schott Glas
  - SiC mirrors have been made up to 3.5-m diam (Herschel)
    - 30-40µm wavefront quality
    - Visible quality 4-m monolithic SiC seems like unnecessary technical risk for NWO
  - Beryllium – available in hexagons of 1.3-m flat-to-flat or petals up to ~ 1.3-m by 1.7-m
    - Cryogenic advantages not applicable for NWO
“Glass” Substrate Material/Blanks are available in 4-m sizes for NWO

- **Corning – fused silica, ULE®**
  - Blanks up to **8+ m** (requires flow-out and stacking of multiple boules)
  - Solid, open back, closed back (waterjetting, low temperature slumping, fritting)
  - Examples – 8+ m Subaru (ULE); 1.4-m ULE AMSD; 1.8-m ULE TDM; 1.45-m Kepler PM; 1.4-m fused silica AMSD; 0.93-m fused silica OSCAR

- **Hextek – borosilicate**
  - 1.5 m gas fusion for borosilicate; **2.5-m** castings for borosilicate
  - Have made 1.5-m pieces; small optic flown on MSTI-3

- **LZOS Lytkarino Optical Glass Factory – AstroSitall**
  - Blank melting facility up to **6-m**
  - AstroSitall crystalline glass ceramic made up to 3.0 m in Russia

- **Schott – Zerodur®**
  - Blanks up to **8+ m** (up to 1.2-m in US; larger in Germany)
  - Solid, open back, partially closed back blanks
  - Examples – 8+ m VLT PMs; 1.9-m GTC PM segments; 1.5-m NMSD (COI); 0.64-m Quickbird/Earthwatch; 0.5-m HIRISE; 2.7-m SOFIA

- **University of Arizona – borosilicate**
  - Blanks up to **8.4 m** formed by spin casting
  - Examples – 2-m NMSD (U of A) mirror; 6.5m and 8m ground based PMs
Lightweighting of Mirror Blanks

- **Criteria**
  - Mass versus stiffness
  - Machineability in reasonable time
  - Residual Stress
  - Mounting features

- **Pocket geometry**
  - Triangles for open back
  - Hexagons for partially closed back (or for completely closed back)
    - To reduce mass left in corner radii
  - Cell size (total or projection through partially closed back) must accommodate insertion of tooling
  - Chamfers
    - Minimize to reduce mass while maintaining minimum to control stress
    - Compatible with nominal vendor tooling
Lightweighting can be performed on 4-m and larger blanks by multiple vendors

<table>
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<tr>
<th>Vendor</th>
<th>Size Capability</th>
<th>LW Machining Experience</th>
<th>Other Capabilities/ Comments</th>
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<tbody>
<tr>
<td>AMOS</td>
<td>3-m</td>
<td>milling, ultrasonic machining; partially closed back</td>
<td></td>
</tr>
<tr>
<td>Axsys</td>
<td>2.5-m x 1.5-m 5-axis Toshiba; 2-m x 1.5-m Mitsui Seiki</td>
<td>milling; open, partially closed back</td>
<td></td>
</tr>
<tr>
<td>Brashear (L-3)</td>
<td>3.5-m 6-axis CNC</td>
<td>milling; open, partially closed back</td>
<td>chemical milling and etching</td>
</tr>
<tr>
<td>Corning</td>
<td>1.5-m 5-axis; 8.4-m 3-axis bridge with tilted spindle</td>
<td>milling; waterjet (up to 3-m); open, closed back</td>
<td>Frit bonding (up to 1.6m) of closed back construction typical approach; 2.4-m low temp. fusion; acid etching up to 2.5-m</td>
</tr>
<tr>
<td>Goodrich</td>
<td>4-m 5-axis Arboga</td>
<td>milling, waterjet; open back</td>
<td>chemical milling and etching</td>
</tr>
<tr>
<td>Inventex, Inc</td>
<td>2-m 3-axis</td>
<td>milling; open, partially closed back</td>
<td></td>
</tr>
<tr>
<td>ITT</td>
<td>3-m</td>
<td>milling, waterjet; open back</td>
<td>Fusion or frit bonding of closed back; corrugated mirrors</td>
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<tr>
<td>LZOS</td>
<td>4-m</td>
<td>milling, waterjet; open back</td>
<td>Frit or frit bonding of closed back; corrugated mirrors</td>
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<tr>
<td>REOSC (Sagem)</td>
<td>3.0 m+</td>
<td>open, partially closed back</td>
<td>chemical milling and etching</td>
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<tr>
<td>Schott</td>
<td>2.0-m 5-axis; 4-m 3 axis</td>
<td>milling; open back; partially closed back</td>
<td>can anneal to stress relieve; pocket etch; 5-m and 10-m annealing furnaces</td>
</tr>
<tr>
<td>SESO</td>
<td>2.5-m 5-axis</td>
<td>milling; partially closed back</td>
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2.7-m SOFIA blank during lightweighting (75%) at REOSC
Mirrors 4-m and up in aperture have been successfully polished

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<th>Heritage Examples</th>
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<td>Brashear (L-3)</td>
<td>8.3-m</td>
<td>Polished 8.3-m Subaru ULE; 1.45-m Kepler ULE</td>
<td>MRF polishing capability being added</td>
</tr>
<tr>
<td>Goodrich</td>
<td>4-m 5-axis Arbogas</td>
<td>Polished HST 2.4-m ULE, Chandra 1.2 m dia x 0.8 m Zerodur</td>
<td></td>
</tr>
<tr>
<td>ITT</td>
<td>3-m 5-axis CNC machine, 2.5-m off-axis gen.</td>
<td>Polished HST 2.4-m ULE back-up mirror</td>
<td>Ion figuring capability</td>
</tr>
<tr>
<td>Opteon</td>
<td>3.5-m+</td>
<td>Polished Herschel 3.5-m mirror</td>
<td></td>
</tr>
<tr>
<td>Rayleigh Optical</td>
<td>2.5-m</td>
<td></td>
<td></td>
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<tr>
<td>REOSC (Sagem)</td>
<td>10-m capacity</td>
<td>Polished NMSD 1.5-m Zerodur, GTC 1.8-m Zerodur, SOFIA 2.7-m Zerodur, six 8-m (Gemini ULE, VLT Zerodur)</td>
<td>Ion figuring capability up to 2.5-m</td>
</tr>
<tr>
<td>SESO</td>
<td>1.4-m</td>
<td></td>
<td>2.5-m capacity in-process</td>
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<tr>
<td>Tinsley SSG (L-3)</td>
<td>1.6-m</td>
<td>Polishing 1.5-m JWST segments</td>
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<td>University of Arizona</td>
<td>8.4-m</td>
<td>NMSD 2.0-m borosilicate, 6.5-m to 8-m ground telescopes</td>
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Coating facilities are available for complex coatings up to 3-4 meters in size.

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<td>AFRL</td>
<td>3.6-m</td>
<td>2.5-m (magnetron sputtering), 3.6-m (evaporative)</td>
</tr>
<tr>
<td>Calar-Alto</td>
<td>4-m</td>
<td>Coated 3.5-m Herschel PM with Al</td>
</tr>
<tr>
<td>Quantum (Denton)</td>
<td>1.5-m; 2.4-m by end of 2008</td>
<td>Will be coating 18 JWST 1.5-m segments with protected gold; protected silver coatings for HST instruments</td>
</tr>
<tr>
<td>Evaporated Metal Films (EMF)</td>
<td>2.4-m</td>
<td></td>
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<tr>
<td>Gemini</td>
<td>8.4-m</td>
<td>8+ m chamber with magnetron sputtering to allow complex protected silver coatings</td>
</tr>
<tr>
<td>GSFC</td>
<td>1.5-m</td>
<td>2-m chamber</td>
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<tr>
<td>ITT</td>
<td>2.4+ m</td>
<td>high reflectance silver, protected aluminum, protected gold</td>
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<tr>
<td>JDS Uniphase</td>
<td>3-m</td>
<td>Chandra optics; e-beam, resistance sources, IAD; DC &amp; RF sputtering</td>
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<td>MSFC SOMTC</td>
<td>4+ m</td>
<td>5.5-m chamber; electron beam, resistive, (sputtering)</td>
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<tr>
<td>REOSC</td>
<td>1.5-m</td>
<td>Looking at adding 2.5-m chamber</td>
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<tr>
<td>Surface Optics Corp.</td>
<td>3-m</td>
<td>Kepler PM (ULE) w/ protected silver; 3.3-m chamber</td>
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<td>University of Arizona</td>
<td>2-m</td>
<td>Chrome &amp; Al deposition w/o overcoatings</td>
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Coating Facilities with 3-m plus capability

- SOMTC 5.5-m (4.57-m clear zone) coating chamber
- Gemini 8-m coating chamber
- Calor Alto 4-m coating chamber with 3.5-m Herschel PM
- Protected-silver coating demonstrated on Kepler 1.45-m flight PM (ULE) – 400-900 nm – coated in SOC chamber
- JDSU 3-m coating chamber

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$$\text{4-leg spider gives 4-fold sidelobes with intensity } < (3.3 \times 10^{-4}) \left( \frac{\lambda}{\mu m} \right)^2 \left( \frac{\theta}{\text{arcsec}} \right)^{-2}$$
$$\text{3-leg spider gives 6-fold sidelobes with 1/4 the intensity: } (8 \times 10^{-5}) \left( \frac{\lambda}{\mu m} \right)^2 \left( \frac{\theta}{\text{arcsec}} \right)^{-2}$$

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Manufacturability

Substrate Material – Zerodur and ULE blanks can be made at 4m size
Lightweighting – Can be performed on 4-m optics by several vendors
Polishing – Can be performed on 4-m optics by several vendors
Optical coating – One vendor identified in continental US for 4-m optics
Material Candidates

- Material properties
  CTE, CTE homogeneity, thermal conductivity, density, stiffness, etc.
  - Thermal gradients expected but rotisserie effects can be avoided
  - Fabrication and test temperatures vs. operating temperature
  - Rigid vs. Semi-rigid vs. Membrane
  - Ease of lightweighting, imposing integral mounting interfaces, polishing

- NWO material candidates
  - ULE®, Zerodur® borosilicate, fused silica – all can be used for up to 4-m monoliths
    • Zerodur® 4-m blank(s) are sometimes in-stock at Schott Glas
  - SiC mirrors have been made up to 3.5-m diam (Herschel)
    • 30-40µm wavefront quality
    • Visible quality 4-m monolithic SiC seems like unnecessary technical risk for NWO
  - Beryllium – available in hexagons of 1.3-m flat-to-flat or petals up to ~ 1.3-m by 1.7-m
    • Cryogenic advantages not applicable for NWO
“Glass” Substrate Material/Blanks are available in 4-m sizes for NWO

- **Corning – fused silica, ULE®**
  - Blanks up to **8+ m** (requires flow-out and stacking of multiple boules)
  - Solid, open back, closed back (waterjetting, low temperature slumping, fritting)
  - Examples – 8+ m Subaru (ULE); 1.4-m ULE AMSD; 1.8-m ULE TDM; 1.45-m Kepler PM; 1.4-m fused silica AMSD; 0.93-m fused silica OSCAR

- **Hextek – borosilicate**
  - 1.5 m gas fusion for borosilicate; **2.5-m** castings for borosilicate
  - Have made 1.5-m pieces; small optic flown on MSTI-3

- **LZOS Lytkarino Optical Glass Factory – AstroSitall**
  - Blank melting facility up to **6-m**
  - AstroSitall crystalline glass ceramic made up to 3.0 m in Russia

- **Schott – Zerodur®**
  - Blanks up to **8+ m** (up to 1.2-m in US; larger in Germany)
  - Solid, open back, partially closed back blanks
  - Examples – 8+ m VLT PMs; 1.9-m GTC PM segments; 1.5-m NMSD (COI); 0.64-m Quickbird/Earthwatch; 0.5-m HIRISE; 2.7-m SOFIA

- **University of Arizona – borosilicate**
  - Blanks up to **8.4 m** formed by spin casting
  - Examples – 2-m NMSD (U of A) mirror; 6.5m and 8m ground based PMs
Lightweighting of Mirror Blanks

- **Criteria**
  - Mass versus stiffness
  - Machineability in reasonable time
  - Residual Stress
  - Mounting features

- **Pocket geometry**
  - Triangles for open back
  - Hexagons for partially closed back (or for completely closed back)
    - To reduce mass left in corner radii
  - Cell size (total or projection through partially closed back) must accommodate insertion of tooling
  - Chamfers
    - Minimize to reduce mass while maintaining minimum to control stress
    - Compatible with nominal vendor tooling
Lightweighting can be performed on 4-m and larger blanks by multiple vendors

<table>
<thead>
<tr>
<th>Vendor</th>
<th>Size Capability</th>
<th>LW Machining Experience</th>
<th>Other Capabilities/ Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMOS</td>
<td>3-m</td>
<td>milling, ultrasonic machining; partially closed back</td>
<td></td>
</tr>
<tr>
<td>Axsys</td>
<td>2.5-m x 1.5-m 5-axis Toshiba; 2-m x 1.5-m Mitsui Seiki</td>
<td>milling; open, partially closed back</td>
<td></td>
</tr>
<tr>
<td>Brashear (L-3)</td>
<td><strong>3.5-m</strong> 6-axis CNC</td>
<td>milling; open, partially closed back</td>
<td>chemical milling and etching</td>
</tr>
<tr>
<td>Corning</td>
<td>1.5-m 5-axis; <strong>8.4-m</strong> 3-axis bridge with tilted spindle</td>
<td>milling; waterjet (up to 3-m); open, closed back</td>
<td>Frit bonding (up to 1.6m) of closed back construction typical approach; 2.4-m low temp. fusion; acid etching up to 2.5-m</td>
</tr>
<tr>
<td>Goodrich</td>
<td>4-m 5-axis Arboga</td>
<td>milling, waterjet; open back</td>
<td>chemical milling and etching</td>
</tr>
<tr>
<td>Inventex, Inc</td>
<td>2-m 3-axis</td>
<td>milling; open, partially closed back</td>
<td></td>
</tr>
<tr>
<td>ITT</td>
<td>3-m</td>
<td>milling, waterjet; open back</td>
<td>Fusion or frit bonding of closed back; corrugated mirrors</td>
</tr>
<tr>
<td>LZOS</td>
<td>4-m</td>
<td>milling, open, partially closed back</td>
<td></td>
</tr>
<tr>
<td>REOSC (Sagem)</td>
<td>3.0 m+</td>
<td>open, partially closed back</td>
<td>chemical milling and etching</td>
</tr>
<tr>
<td>Schott</td>
<td>2.0-m 5-axis; <strong>4-m</strong> 3 axis</td>
<td>milling; open back; partially closed back</td>
<td>can anneal to stress relieve; pocket etch; 5-m and 10-m annealing furnaces</td>
</tr>
<tr>
<td>SESO</td>
<td>2.5-m 5-axis</td>
<td>milling; partially closed back</td>
<td></td>
</tr>
</tbody>
</table>

2.7-m SOFIA blank during lightweighting (75%) at REOSC
Mirrors 4-m and up in aperture have been successfully polished

<table>
<thead>
<tr>
<th>Vendor</th>
<th>Size Capability</th>
<th>Heritage Examples</th>
<th>Other Capabilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brashear (L-3)</td>
<td>8.3-m</td>
<td>Polished 8.3-m Subaru ULE; 1.45-m Kepler ULE</td>
<td>MRF polishing capability being added</td>
</tr>
<tr>
<td>Goodrich</td>
<td>4-m 5-axis Arbogas</td>
<td>Polished HST 2.4-m ULE, Chandra 1.2 m dia x 0.8 m Zerodur</td>
<td></td>
</tr>
<tr>
<td>ITT</td>
<td>3-m 5-axis CNC machine, 2.5-m off-axis gen.</td>
<td>Polished HST 2.4-m ULE back-up mirror</td>
<td>Ion figuring capability</td>
</tr>
<tr>
<td>Opteon</td>
<td>3.5-m+</td>
<td>Polished Herschel 3.5-m mirror</td>
<td></td>
</tr>
<tr>
<td>Rayleigh Optical</td>
<td>2.5-m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>REOSC (Sagem)</td>
<td>10-m capacity</td>
<td>Polished NMSD 1.5-m Zerodur, GTC 1.8-m Zerodur, SOFIA 2.7-m Zerodur, six 8-m (Gemini ULE, VLT Zerodur)</td>
<td>Ion figuring capability up to 2.5-m</td>
</tr>
<tr>
<td>SESO</td>
<td>1.4-m</td>
<td></td>
<td>2.5-m capacity in-process</td>
</tr>
<tr>
<td>Tinsley SSG (L-3)</td>
<td>1.6-m</td>
<td>Polishing 1.5-m JWST segments</td>
<td></td>
</tr>
<tr>
<td>University of Arizona</td>
<td>8.4-m</td>
<td>NMSD 2.0-m borosilicate, 6.5-m to 8-m ground telescopes</td>
<td></td>
</tr>
</tbody>
</table>
Coating facilities are available for complex coatings up to 3-4 meters in size

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<tr>
<th>Vendor</th>
<th>Size Capability</th>
<th>Heritage Examples and other capabilities</th>
</tr>
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<tbody>
<tr>
<td>AFRL</td>
<td>3.6-m</td>
<td>2.5-m (magnetron sputtering), 3.6-m (evaporative)</td>
</tr>
<tr>
<td>Calar-Alto</td>
<td>4-m</td>
<td>Coated 3.5-m Herschel PM with Al</td>
</tr>
<tr>
<td>Quantum (Denton)</td>
<td>1.5-m; 2.4-m by end of 2008</td>
<td>Will be coating 18 JWST 1.5-m segments with protected gold; protected silver coatings for HST instruments</td>
</tr>
<tr>
<td>Evaporated Metal Films (EMF)</td>
<td>2.4-m</td>
<td></td>
</tr>
<tr>
<td>Gemini</td>
<td>8.4-m</td>
<td>8+ m chamber with magnetron sputtering to allow complex protected silver coatings</td>
</tr>
<tr>
<td>GSFC</td>
<td>1.5-m</td>
<td>2-m chamber</td>
</tr>
<tr>
<td>ITT</td>
<td>2.4+ m</td>
<td>high reflectance silver, protected aluminum, protected gold</td>
</tr>
<tr>
<td>JDS Uniphase</td>
<td>3-m</td>
<td>Chandra optics; e-beam, resistance sources, IAD; DC &amp; RF sputtering</td>
</tr>
<tr>
<td>MSFC SOMTC</td>
<td>4+ m</td>
<td>5.5-m chamber; electron beam, resistive, (sputtering)</td>
</tr>
<tr>
<td>REOSC</td>
<td>1.5-m</td>
<td>Looking at adding 2.5-m chamber</td>
</tr>
<tr>
<td>Surface Optics Corp.</td>
<td>3-m</td>
<td>Kepler PM (ULE) w/ protected silver; 3.3-m chamber</td>
</tr>
<tr>
<td>University of Arizona</td>
<td>2-m</td>
<td>Chrome &amp; Al deposition w/o overcoatings</td>
</tr>
<tr>
<td>Zeiss</td>
<td>2.3-m</td>
<td></td>
</tr>
</tbody>
</table>
Coating Facilities with 3-m plus capability

- SOMTC 5.5-m (4.57-m clear zone) coating chamber
- Gemini 8-m coating chamber
- Calor Alto 4-m coating chamber with 3.5-m Herschel PM
- SOC 3.3-m coating chamber
- Protected-silver coating demonstrated on Kepler 1.45-m flight PM (ULE) – 400-900 nm – coated in SOC chamber
- JDSU 3-m coating chamber