4-m NWO Telescope Design

Steve Kendrick

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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

	Requirement	Goal
Science passband	0.5–1.0µm	0.1–1.5µm
Engineering passband	1.5–2.3µm	1.5–3µm
Fields of view		
Planet detection	5×5 arcsec	20×20 arcsec
Planet spectroscopy	1×1 arcsec	10×3 arcsec
Wide field camera	3×3 arcmin	20×20 arcmin
Engineering	3×3 arcmin	

Characteristic	Value	Remarks
Telescope architecture	Obscured	No science constraints
Instrument pickoffs	Field-angle division; WFcam at TMA, all others at Cassegrain	Minimize reflections for UV & exoplanets
Mirror coatings	Al/MgF_2 for PM & SM; Silver for later optics	Throughput for UV and exoplanets
PM architecture	Monolithic	Topic for future trade
Telescope solar shield	Fixed with cover	Fits in Atlas-V shroud
Operating temperature	Ambient (~25°C)	Thermal stability, I&T

Future Trades for Primary Mirror

- Segmentation and construction options

	Monolithic	Segmented
Rigid mirror	Kinematic /whiffle-tree	6-DOF actuators
Semi-rigid mirror	Dozens of actuators	6-DOF plus curvature
Flexible meniscus	100s to 1000s of actuators	Dozens of actuators per segment

- 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

4-leg spider gives 4-fold sidelobes with intensity $< (3.3\times10^{-4})\ (\lambda/\mu m)^2\ (\theta/arcsec)^{-2}$
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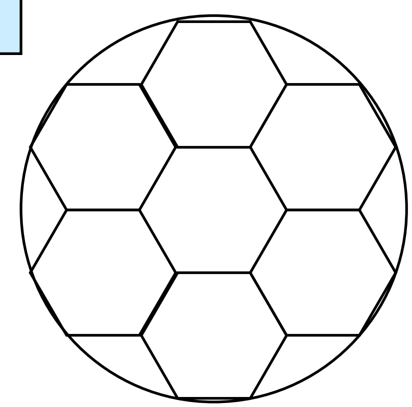
- PM segment scatter from stars outside the telescope FOV

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

  - 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

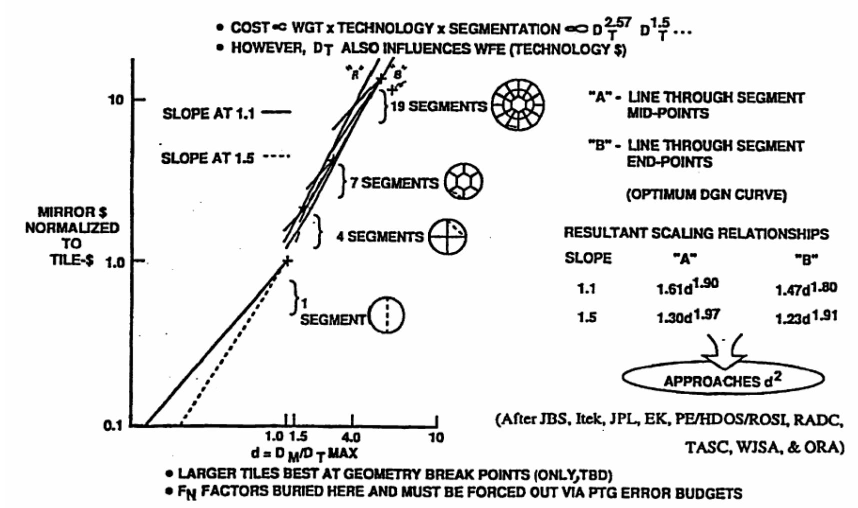
- Mass is driven by required mirror stiffness and gravity sag during tests
  - For a given stiffness, segments have lower areal density than monolithic PM
  - Must include actuator mass and backplanes appropriate for each mirror type
- Stiffness requirements can be very different
  - Rigid PM ➔ must 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

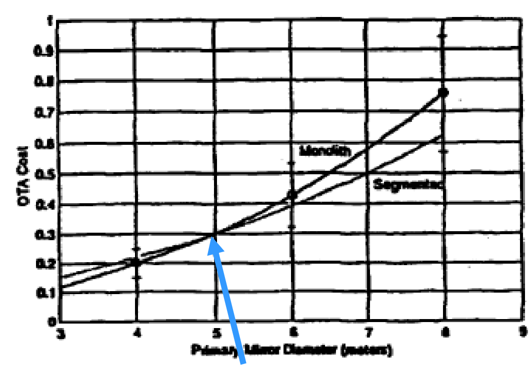
- Assume PM comprises 6 segments
  - More segmentation requires more unique prescriptions and higher total costs
- At least 7 DOF actuation / segment
  - RoC actuator for fabrication variability
  - Hexapod for rigid body alignment
  - Future trade on higher number of actuators
- Requires a wavefront 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 ➔ ~4m
For a 9-segment vs. monolithic PM ➔ ~5m



5-m cross-over point

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

Schott 2.8-m Zerodur blank

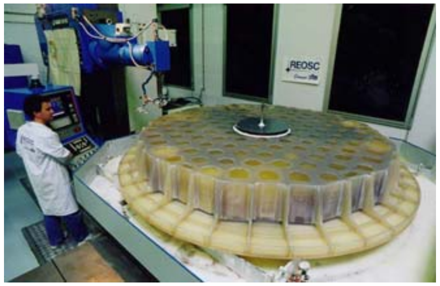
U of A Spin Cast Furnace and resulting 3.8-m borosilicate blank

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

Vendor	Size Capability	LW Machining Experience	Other Capabilities/ Comments
AMOS	3-m	milling, ultrasonic machining; partially closed back	
Axsys	2.5-m x 1.5-m 5-axis Toshiba; 2-m x 1.5-m Mitsui Seiki	milling; open, partially closed back	chemical milling, chemical etching, thermal cycling
Brashear (L-3)	3.5-m 6-axis CNC	milling; open, partially closed back	chemical milling and etching
Corning	1.5-m 5-axis; 8.4-m 3-axis bridge with tilted spindle	milling; waterjet (up to 3-m); open, closed back	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
Goodrich	4-m 5-axis Arboga	milling, waterjet; open back	chemical milling and etching
Inventex, Inc	2-m 3-axis	milling; open, partially closed back	
ITT	3-m	milling, waterjet; open back	Fusion or frit bonding of closed back; corrugated mirrors
LZOS	4-m	milling; open, partially closed back	
REOSC (Sagem)	3.0 m+	open, partially closed back	chemical milling and etching
Schott	2.0-m 5-axis; 4-m 3 axis	milling; open back; partially closed back	can anneal to stress relieve; pocket etch; 5-m and 10-m annealing furnaces
SESO	2.5-m 5-axis	milling; partially closed back	



2.7-m SOFIA blank during lightweighting (75%) at REOSC

Mirrors 4-m and up in aperture have been successfully polished

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


REOSC polishers up to 8+ m


U of Arizona 8.4-m polisher


L3 Brashear 8.5-m polisher


L3 Tinsley JWST polishers (8 machines)

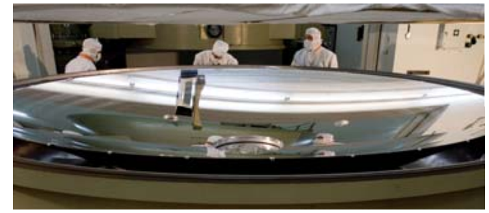
Coating facilities are available for complex coatings up to 3-4 meters in size

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

Coating Facilities with 3-m plus capability

SOMTC 5.5-m (4.57-m clear zone) coating chamber

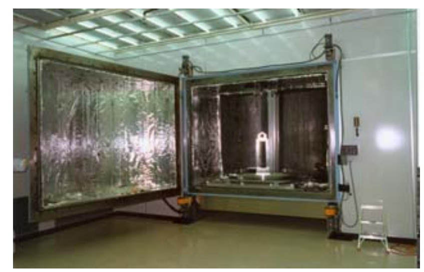
Gemini 8-m coating chamber



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

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Semi-rigid mirror	Dozens of actuators	6-DOF plus curvature
Flexible meniscus	100s to 1000s of actuators	Dozens of actuators per segment

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  - Geometry
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  - Both capable of 4 m monolith
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Stray light from diffraction sidelobes

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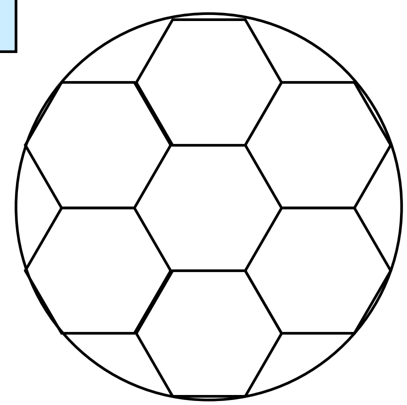

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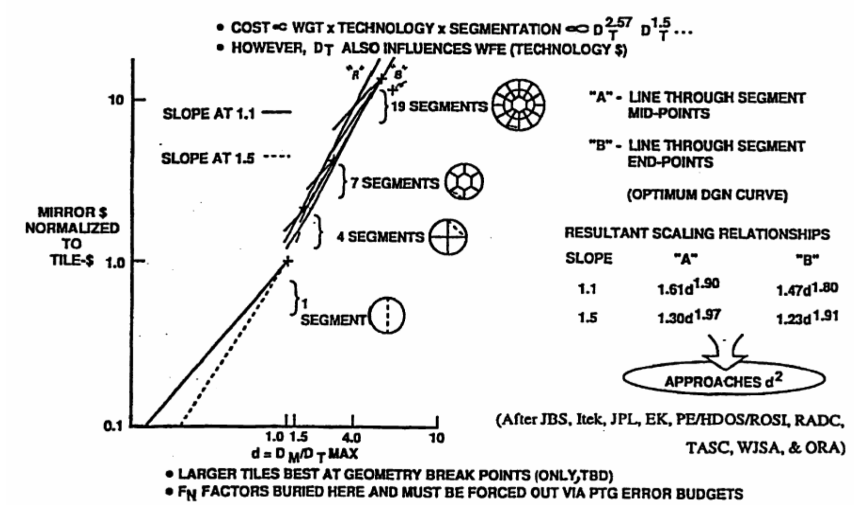

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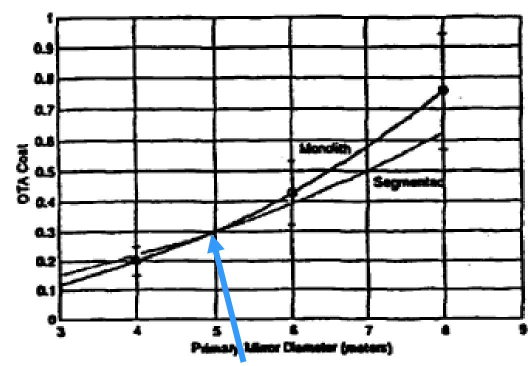

5-m cross-over point

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  - SiC mirrors have been made up to 3.5-m diam (Herschel)
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- 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

Schott 2.8-m Zerodur blank

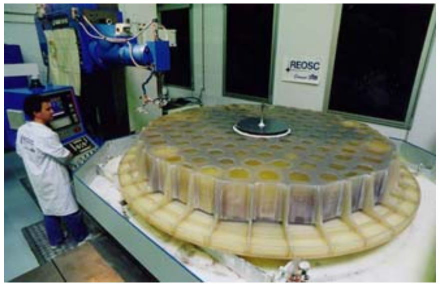
U of A Spin Cast Furnace and resulting 3.8-m borosilicate blank

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

Vendor	Size Capability	LW Machining Experience	Other Capabilities/ Comments
AMOS	3-m	milling, ultrasonic machining; partially closed back	
Axsys	2.5-m x 1.5-m 5-axis Toshiba; 2-m x 1.5-m Mitsui Seiki	milling; open, partially closed back	chemical milling, chemical etching, thermal cycling
Brashear (L-3)	3.5-m 6-axis CNC	milling; open, partially closed back	chemical milling and etching
Corning	1.5-m 5-axis; 8.4-m 3-axis bridge with tilted spindle	milling; waterjet (up to 3-m); open, closed back	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
Goodrich	4-m 5-axis Arboga	milling, waterjet; open back	chemical milling and etching
Inventex, Inc	2-m 3-axis	milling; open, partially closed back	
ITT	3-m	milling, waterjet; open back	Fusion or frit bonding of closed back; corrugated mirrors
LZOS	4-m	milling; open, partially closed back	
REOSC (Sagem)	3.0 m+	open, partially closed back	chemical milling and etching
Schott	2.0-m 5-axis; 4-m 3 axis	milling; open back; partially closed back	can anneal to stress relieve; pocket etch; 5-m and 10-m annealing furnaces
SESO	2.5-m 5-axis	milling; partially closed back	



2.7-m SOFIA blank during lightweighting (75%) at REOSC

Mirrors 4-m and up in aperture have been successfully polished

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


REOSC polishers up to 8+ m


U of Arizona 8.4-m polisher


L3 Brashear 8.5-m polisher


L3 Tinsley JWST polishers (8 machines)

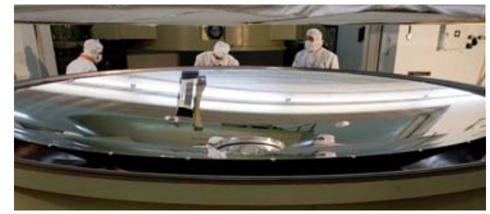
Coating facilities are available for complex coatings up to 3-4 meters in size

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

Coating Facilities with 3-m plus capability

SOMTC 5.5-m (4.57-m clear zone) coating chamber

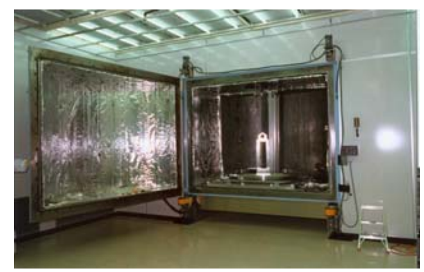
Gemini 8-m coating chamber



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