Lynx Mirror Architecture Trade – Recommendation to Lynx STDT Chairs

Presenters: Gary Blackwood, NASA JPL/Caltech
Jessica Gaskin, NASA MSFC
Rita Sambruna, NASA HQ
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Paul Reid/Eric Schwartz, SAO
Jaya Bajpayee, NASA Ames

July 31, 2018

Outline of Presentation

- Purpose of Study
- Executive Summary
- Trade Process: Consensus via Kepner-Tregoe Method
- Evaluation Criteria
- Option Descriptions: Lynx Mirror Technologies
- Trade Results: Musts, Wants, Risks, Opportunities
  - Science, Technical, Programmatic Evaluations
  - Dissenting Opinion
- Final Recommendation, Accounting for Risks and Opportunities
- Feasibility
- Next Steps to Final Report
- Backup:
  - Trade Matrix (Handout)
  - TRL Definitions
- Links to Key Supporting Documents

Purpose of Study

- Why conduct this trade, and why now?

- Charter from STDT chairs calls for a recommendation for "one Primary Mirror Optical Assembly architecture to focus the design for the final report and identify any feasible alternates."

- The Lynx Mirror Architecture Trade (LMAT) Working Group represents scientific and technical leadership across academia, NASA, and industry

- Full signed charter: [Lynx Optics Trade Study]

Lynx Mirror Assembly Trade – Charter
2/2/2018

A. Background

Lynx is one of four large mission concepts studies funded by the NASA Astrophysics Division for development by a Science and Technology Definition Team (STDT).[1] Recently, the Lynx Red Team recommended that a down-select plan be created for the mirror and gratings technologies in time to make choices for the final report. The Lynx Science and Technology Definition Team (STDT) recognizes that a credible and feasible path to maturing the Lynx mirror assembly is crucial to a compelling and executable Lynx mission concept. Therefore, following deliberations within the Lynx Optics Working Group (OWG) and Study Office and corroborated by the Lynx Red Team recommendations, the STDT commissions a trade study to recommend a reference mirror design that demonstrates a technological path to realizing the science envisioned by the STDT. This document charters the plan for the trade study deliverables, trade process and membership. The goal for completion of the trade study is July 13 2018 in support of Milestone M6 (draft final report) as required in the Management Plan for the Decadal Large Mission Studies[2].

B. Deliverables

The Lynx Mirror Assembly Trade (LMAT) Working Group is chartered by the Lynx STDT to deliver to the Lynx STDT Chairs by the goal of July 13 2018 a recommendation for one Primary Optical Assembly architecture to focus the design for the final report and identify any feasible alternates. The LMAT Working Group participation is defined in Section C.

The recommended option, upon review by STDT and acceptance by the STDT Chairs, will serve as the reference design for the Lynx mission concept for Milestone M6. All other feasible architectures identified in the trade process will be included in the Lynx Technical Roadmap.

* * *

Feryal Ozel
STDT Chair, Lynx
Professor of Astronomy
University of Arizona

Digitally signed by Alexey Vikhlinin
Date: 2018.02.05 15:42:32 -05'00'

Alexey Vikhlinin
STDT Chair, Lynx
Deputy Associate Director, High Energy Astrophysics Division
Harvard-Smithsonian Center for Astrophysics

Decision Statement

- Updated at first Face-to-Face meeting of the Lynx Mirror Architecture Trade (LMAT) Working Group, concurred by LMAT Steering Group:

Recommend **one DRM concept** Mirror Optical Assembly Architecture **to focus the design** for the final report and **identify any feasible alternates.**

Executive Summary

- **Intended Results of this Briefing:**
  - Provide one Primary Mirror Optical Assembly architecture to focus the design for the final report and identify any feasible alternates
  - Provide a recommendation to the Lynx Science and Technology Definition Team (STDT) Chairs and ultimately to the full STDT
- **Executive Summary:**
  - Community working group conducted an open, science, technical, and programmatic evaluation using public evaluation criteria in a series of telecons and F2F meetings since January 2018
  - We reached a broad consensus on the recommendation and the basis for the recommendation
    - Large and diverse team from industry, universities, and multiple NASA Centers
    - ~ 5,000 person-hours over 6 months
    - ~100 documents produced (~650 pages of material)

Recommendation: **The LMAT recommends the Silicon Meta Shell as the DRM concept Mirror Optical Assembly Architecture to focus the design for the Final Report. Full Shell and Adjustable Optics are determined to be feasible alternates.**

- Evaluation criteria that drove the recommendation included the current and near-future demonstrated performance and technology maturation roadmaps. Relative simplicity of mirror assembly production process and test and Relative impact of technical accommodation to the spacecraft were also discriminating factors.
- **The consensus recommendation held when assessed against risks and opportunities**.

Executive Summary (2)

	Adjustable	Full Shell	Silicon Meta-Shell
Advantages	- Adjustability potential enables shorter production and installation timelines - Can correct errors introduced after mirrors are through fabrication	- Potential to have the shortest telescope delivery schedule	- Most mature technology - Shortest path to achieving TRL-5 and TRL-6 - Uses the shortest mirrors, which leads to improved off-axis PSF performance
Disadvantages	- Many steps in the process have yet to be demonstrated - Control needs to be demonstrated at the system level, increasing test time	- Challenge of producing very thin, high quality mirrors up to 3m diameter - Greatest mass	- 3x to 100x quantity of mirrors to produce, align, and bond results in longest schedule

NASA Headquarters Observations

NASA HQ observed the LMAT prioritization process during the 6 months of the task, finding that it was conducted and executed with fairness, integrity, and inclusiveness. When present, biases and conflicts of interest were acknowledged and mitigated.

Rita M. Sambruna
Astrophysics Division
Science Mission Directorate
NASA Headquarters

Bias Mitigation included:

- Ensuring a transparent trade process
- Enacting a consensus policy that allowed for dissent
- Maintaining a practice of reaching consensus by investing in group discussion, capturing risks and opportunities in the trade

Gary Blackwood, NASA JPL
Exoplanet Exploration Program Office

TRADE PROCESS: CONSENSUS VIA KEPNER-TREGOE METHOD

Trade Process

- A structured rational decision process is useful when:
  - A decision has to be made
  - The stakes are high
  - Timeliness, transparency, communication, and documentation are important
  - The decision needs to stick (consensus is important)
  - Other methods (such as declaration, voting) won't work
- Best-practices format is the Kepner-Tregoe method for rational decision making
  - Fundamentally one page, promotes transparency and communication, invites consensus and creativity
  - Around since the 1950's, see *The Rational Manager*, Kepner and Tregoe, 1965
- Used in the past several years in similar NASA Astrophysics studies

Features of Kepner-Tregoe Decision Process

- Adapted from Kepner-Tregoe methods. The Rational Manager, Kepner and Trego, 1965
- A systematic approach for decision making

Decision Statement									
				Option 1		*Option 2*		*Option 3*	
Description		*Feature 1*							
		Feature 2							
		Feature 3							
Evaluation	**Musts**								
		M1		✔		✔		✔	
		M2		✔		**?**		**?**	
		M3		✔		✔		✘	
	Wants	*Weights*							
		W1	*w1%*	*Rel score*		*Rel score*		*Rel score*	
		W2	*w2%*	*Rel score*		*Rel score*		*Rel score*	
		W3	*w3%*	*Rel score*		*Rel score*		*Rel score*	
		100%	Wt sum =>	*Score 1*		*Score 2*		*Score 3*	
	Risks			C	L	C	L	C	L
		Risk 1		M	L	M	L		
		Risk 2		H	H	M	M		
Final Decision, Accounting for Risks									

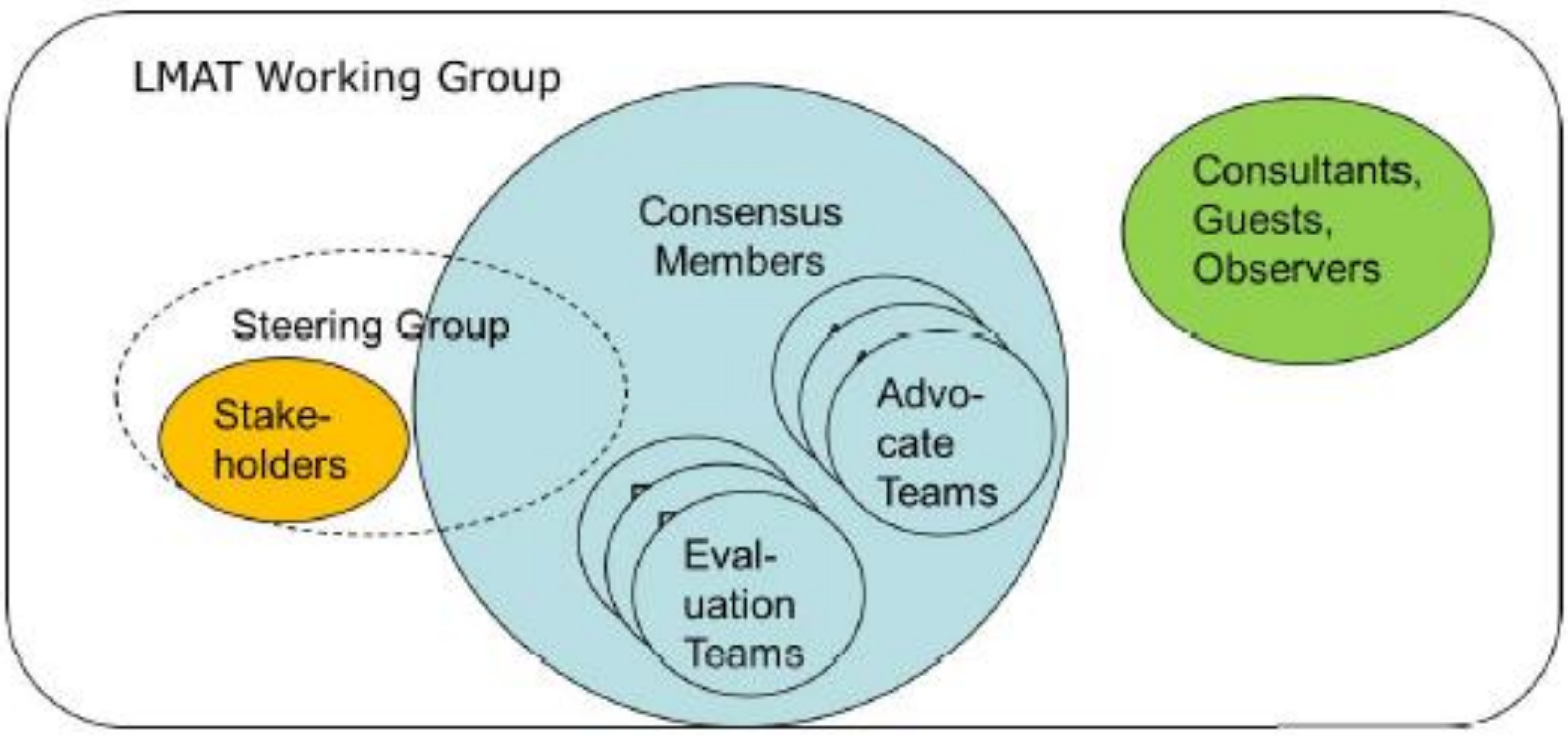
C = Consequence, L = Likelihood

Process Overview

- Agree on **Evaluation Criteria** and **Weights**
- Document **Options** and **Description**
- **Evaluate** Options vs Criteria
- Reach **Consensus** on Evaluation
- Document **Risks, Opportunities**
- **Recommendation** accounting for Risks, Opportunities

A little consensus at a time

The LMAT Working Group



LMAT: Lynx Mirror Architecture Trade

LMAT Working Group Participants

Consensus Group

Member at Large

1. Mark Schattenburg	MIT	

Advocates

2. Kiranmayee Kilaru	USRA / MSFC	Full Shell
3. Giovanni Pareschi	INAF / OAB	Full Shell
4. William Zhang	NASA GSFC	Silicon Meta-shell
5. Peter Solly	NASA GSFC	Silicon Meta-shell
6. Paul Reid	Harvard SAO	Adjustable Segmented
7. Eric Schwartz	Harvard SAO	Adjustable Segmented

Science Evaluation Team (SET)

8. Frits Paerels	Columbia Univ.	**SET Lead**
9. Daniel Stern	NASA JPL	
10. Ryan Hickox	Dartmouth	

Technical Evaluation Team (TET)

11. Gabe Karpati	NASA GSFC	**TET Lead**
12. Ryan McClelland	NASA GSFC	
13. Lester Cohen	Harvard SAO	
14. Gary Matthews	ATA Aerospace, LLC	
15. Mark Freeman	Harvard SAO	
16. David Broadway	NASA MSFC	
17. David Windt	Reflective X-ray Optics	
18. Marta Civitani	INAF / OAB	
19. Paul Glenn	Bauer Associates, Inc.	
20. Ted Mooney	Harris	
21. Jon Arenberg	NGAS	
22. Chip Barnes/Bill Purcell	Ball	

Programmatic Evaluation Team (PET)

22. Jaya Bajpayee	NASA ARC	**PET Lead**
23. John Nousek	Penn State	
24. Karen Gelmis	NASA MSFC	
25. Steve Jordan	Ball	
26. Charlie Atkinson	NGAS	

Subject Matter Experts, Observers and Guests

Denise Podolski	NASA STMD
Rita Sambruna	NASA HQ
Terri Brandt	NASA PCOS
Vadim Burwitz	MPE
Susan Trolier-McKinstry	Penn State
Casey DeRoo	U. Iowa
Kurt Ponsor	Mindrum/Optics Working Group
Dan Schwartz	SAO/Optics Working Group
Steve Bongiorno	MSFC

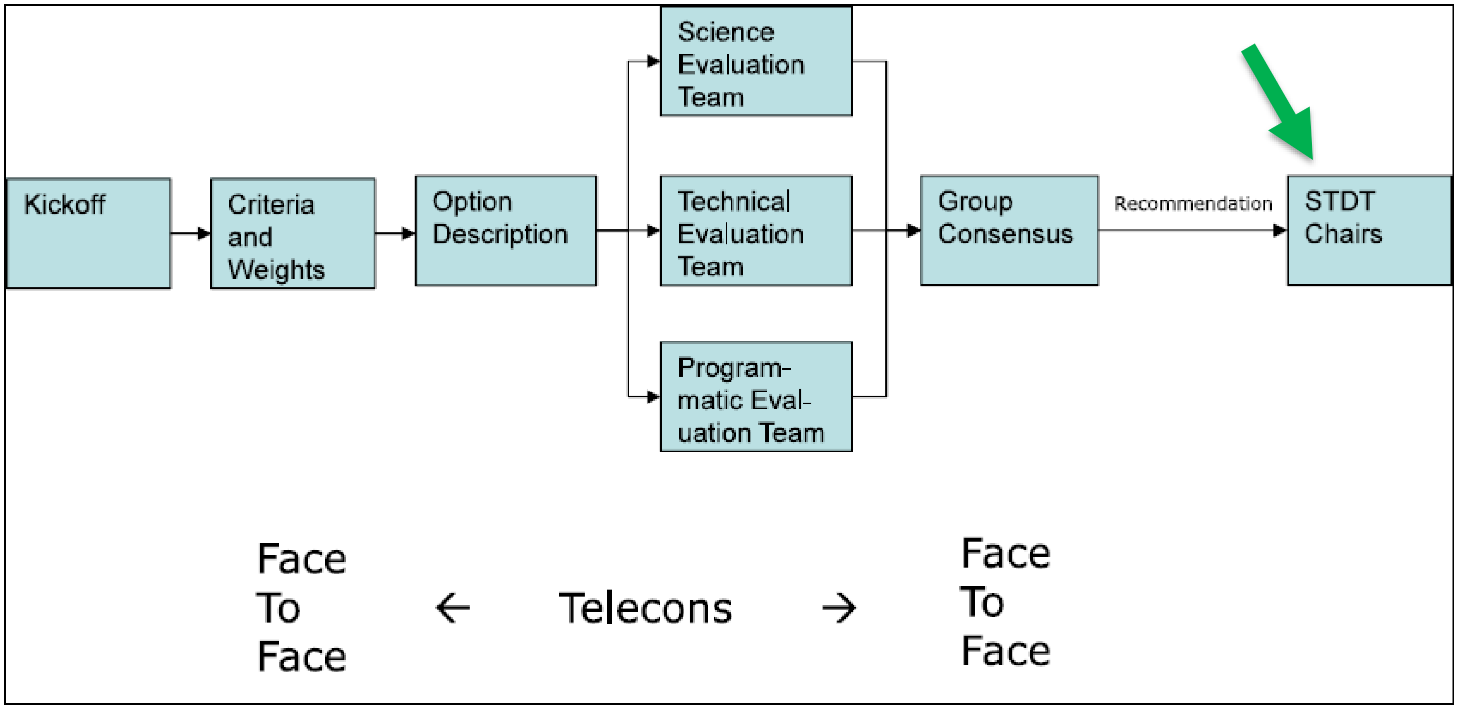
Steering Group

Feryal Özel	University of Arizona
Alexey Vikhlinin	Harvard SAO
Jessica Gaskin	NASA MSFC
Robert Petre	NASA GSFC
Doug Swartz	NASA MSFC
Jon Arenberg	NGAS
Bill Purcell	Ball
Lynn Allen	Harris
Jaya Bajpayee	NASA ARC
Gabe Karpati	NASA GSFC
Frits Paerels	Columbia University
Mark Schattenburg	MIT

Facilitator

Gary Blackwood — NASA ExEP/ JPL

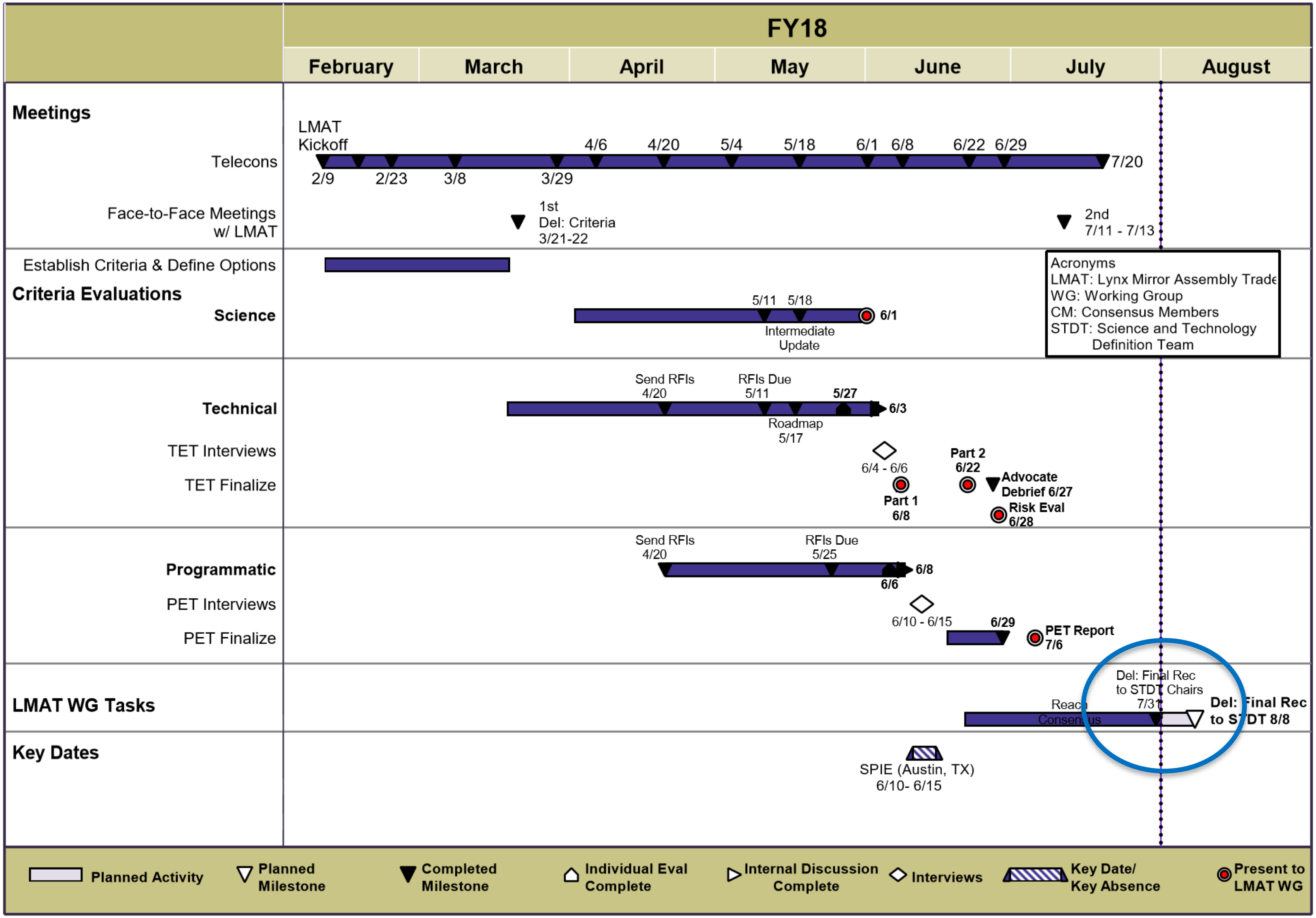
LMAT Working Group - Work Flow



LMAT Tier 1

* Tentative Dates

Rev. 2018 Jul 31



Consensus

- Drawn from NASA Policy
- Consensus decisions
  - May produce more durable decisions than those by votes or decree.
  - However, convergence time can be a factor.
- We adopt a Constrained Consensus method defined as: *Strive for consensus in the reasonable time available, else, the leaders make a decision. Dissent (if any) is captured and the group moves on with full support of the decision.*
- Follow 7120.5E, Chapter 3.4, "Process for Handling Dissenting Opinion"
  - Three options:
    - (1) Agree,
    - (2) Disagree but fully support the decision,
    - (3) Disagree and raise a dissenting opinion
  - Treat (1) and (2) as consensus for LMAT Working Group
  - Dissents (3) if any will be documented and delivered to Chairs and to NASA APD management

How we Reached Consensus

- Reached consensus, a little at a time
- Row-by-row evaluation invited consideration of risks (and opportunities) and balancing of the evaluation by all LMAT consensus members
- Adjective scoring first, then numerical
- How we used risks and opportunities:
  - Treated differently than weighted Wants. Instead we stood back from the weighted scoring and asked:
    - When we fully factor in risks and opportunities do we instead consider the second-highest scoring option for the recommendation?
    - This is the traditional Kepner-Tregoe method
- "Use the Matrix – Don't let the Matrix use Us"

Gary Blackwood, NASA JPL

Exoplanet Exploration Program Office

EVALUATION CRITERIA

Trade Process

- Musts and Wants arrived at by consensus and first face-to-face meeting
- Wants were weighted by consensus (out of 100 points)
- Described the features of an outcome that would minimally (or, if more than one) best satisfy the decision statement:

Recommend **one DRM concept** Mirror Optical Assembly Architecture **to focus the design** for the final report and **identify any feasible alternates**

LMAT Musts

- These are pass-fail

Musts		Y/?/N	
	Science		
M1	Optical performance will meet requirements flowing down from Science Trace Matrix		effective area, energy band pass, FOV, grasp (FOV * EA, for ~1" HPD = 600m^2 arcmin^2), angular resolution,
	Technical		
M2	Credible roadmap from today's status to predict flight on-orbit performance		should include scalability to flight dimensions
M3	Performance modeling tools related to current results are demonstrated to be credible		define relative risk of the types of tools considered
M4	Repeatable fabrication process based on current status		
M5	Credible error budget that flows down to each mirror element		Credible - allocation vs estimated capability with realistic and justifiable analyses, includes on-orbit disturbances
M6	Expected to survive launch		
	Programmatic		
M7	Show a credible plan to meet TRL 4-6		by Jessica TRL definition and Karen Project schedule
M8	Produce the mirror assembly within the Program schedule allocation		

LMAT Wants

- The Wants are weighted
- Options are evaluated (relative to one another)

Eight Wants comprise 78 points out of 100

Referred to as 'Key Wants'

Wants		Weight	
	Science		
	Technical 74		
W1	Hightest predicted technology readiness at Astro2020 by March 2020	12	
W2	Relative demonstrated performance	12	
W3	Relative credibility of roadmaps from today's status to predict flight on-orbit performance (reflected M2)	12	
W4	Relative simplicity of mirror assembly production process and test	10	LMA AI&T
W5	Relative contamination control (cost, complexity)	1	
W6	Relative ease of implementing stray light control	3	STDT Guidance
W7	Relative ease of implementing thermal control and baffling	4	fabrication and alignment
W8	Relative ease of creating a system option for charged particle mitigation	1	fabrication and alignment
W10	Relative confidence in launch survivability (reflected M6)	3	must meet all NASA requirements in std-5001a
W11	Relative complexity and accuracy of ground calibration of mirror assembly	6	STDT needs to address what calibration requirement is needed. Within Program schedule allocation. Must include modeling, error budget, etc. If a new facility is proposed
W13	Relative impact of technical accommodation (cost, mass, spacecraft resources, etc...)	10	interfaces, integration, calibration facilities, etc..
	Programmatic 26		
W14	Lowest relative cost to reach TRL5 and 6	3	
W12	Relative cost and credibility of grass-roots cost estimate of the mirror assembly through delivery	10	relative ability of the architecture to provide a BOE. Need to define how cost is defined via WBS. Need informal CATE to determine? + CAN task
W16	Best assessment of the cost of ground calibration of mirror assembly	3	general resources vs dollars
W17	Earliest date to reach TRL5 and 6	4	
W18	Best assessment of the schedule to mirror assembly delivery (reflects M8)	6	
	Total Weights	100	

Evaluation Process

- For the Musts and Wants
- The Trade Matrix needs a **Y/N rating for each MUST** and an **ADJECTIVE RANKING** for each **WANT**
- Provide for every Evaluation a **BASIS with Justification**
  - **Basis:** can be **technical value** (e.g. mass, measured performance, etc.) or the **informed opinion** of the expert evaluator (based on experience, technical judgement, etc.)
- Evaluation Team **Champions** make the preliminary Adjective Rankings
  - Aim for (but not require) entire Evaluation Team consensus.
  - Bring to full LMAT in telecon or F2F#2.
- **Facilitator** leads the entire LMAT to consensus, else document dissent

Evaluation of Musts

- Each **Must** requires Y/N rating and basis
- Champion may choose “**Unknown**” if the basis is uncertain for clear Y/N rankings
  - “U” rating would indicate “no known showstopper”
- The **Conditions** for “U or Y” rating may be captured as a **Risk**
  - You usually know a K-T risk when you hear it
  - Typically that which follows “**but**”, “**unless**”, “**if**”, “**as long as**” during evaluation discussions

Evaluation of Wants

- **Adjective Rankings**
  - The option that is strongest on that criteria is marked "**Best**". Others can be a "**Wash**" and also scored as "Best"
  - Always Score down by adjective ("**Small Difference**", "**Significant Difference**", **or "Very Large Difference"**)
- **Numerical Scoring per Kepner-Tregoe**
  - **Best always gets a 10. Wash = Best = 10.**
  - **Always score down from 10. Small Difference:** 8 or 9**. Significant Difference:** 4 through 7**. Very Large Difference:** 1 through 3

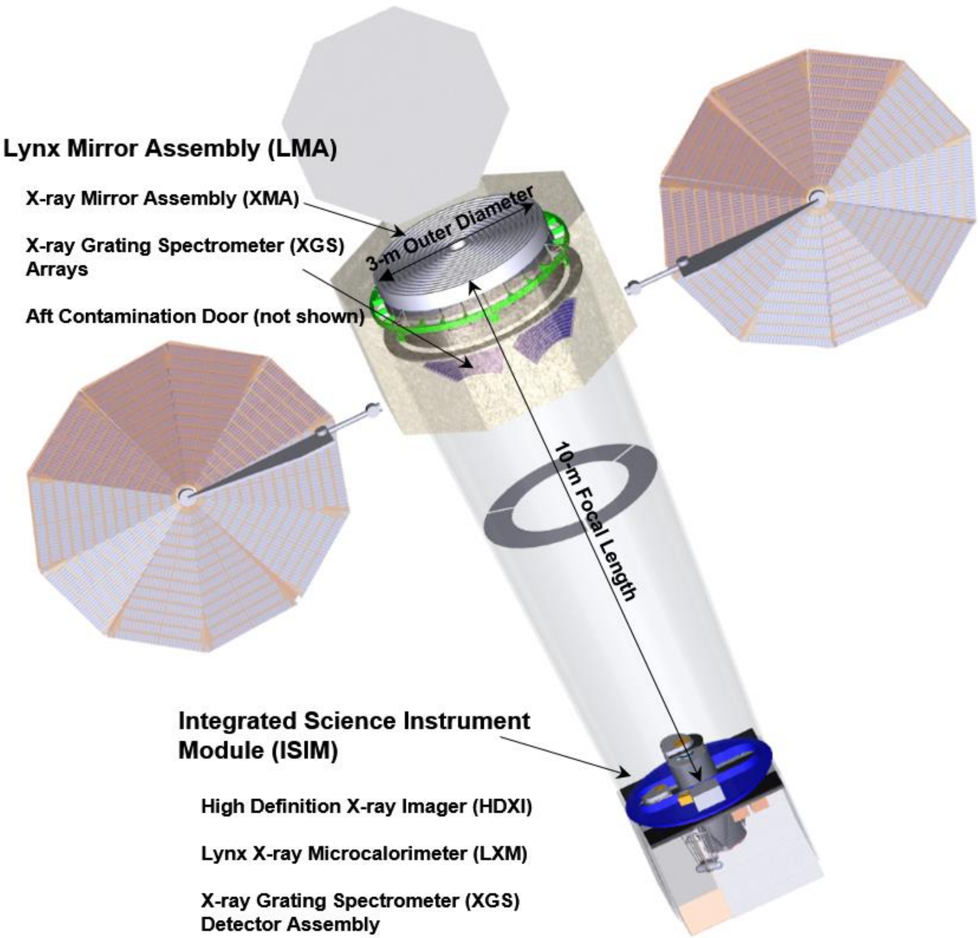
Best=Wash	10
Sm Diff	8-9
Sig Diff	5-6
VL Diff	0-3

Jessica Gaskin, NASA MSFC
Lynx Study Scientist

OPTION DESCRIPTIONS: LYNX MIRROR TECHNOLOGIES

Lynx Requirements

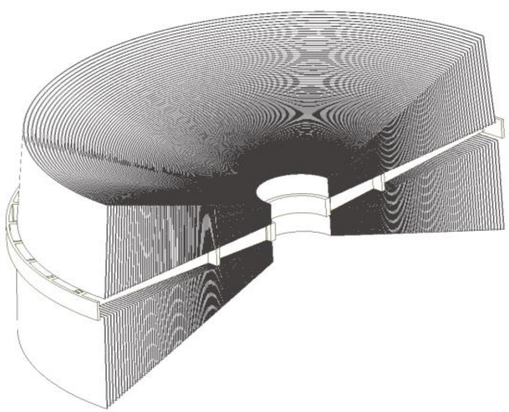
Parameter	Requirement
HEW (On Axis)	0.5 ″
Effective are (On-Axis)	2 m^2
Field Of View (FOV)	10 arcmins radius
Grasp (HEW<1″, E=1keV)	> 600 m^2 * $arcmin^2$
Maximum diameter	3 m
Focal Length	10 m
Max mirror assembly mass	2500 kg

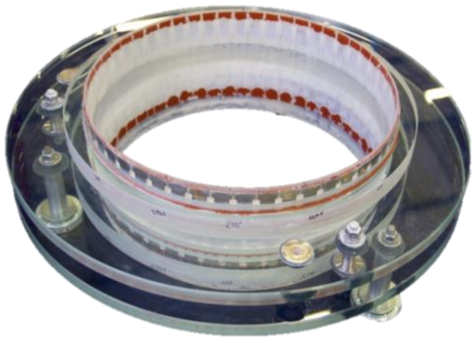


Full Shell Optical Assembly

- M.Civitani, G. Vecchi, J. Holysko, S.Basso, M.Ghigo, G.Pareschi, (INAF-OAB)
- G.Parodi (BCV progetti), G.Toso (INAF-IASF)
- K. Kiranmayee , J. Davis, R. Elsner D. Swartz (MSFC/USRA)

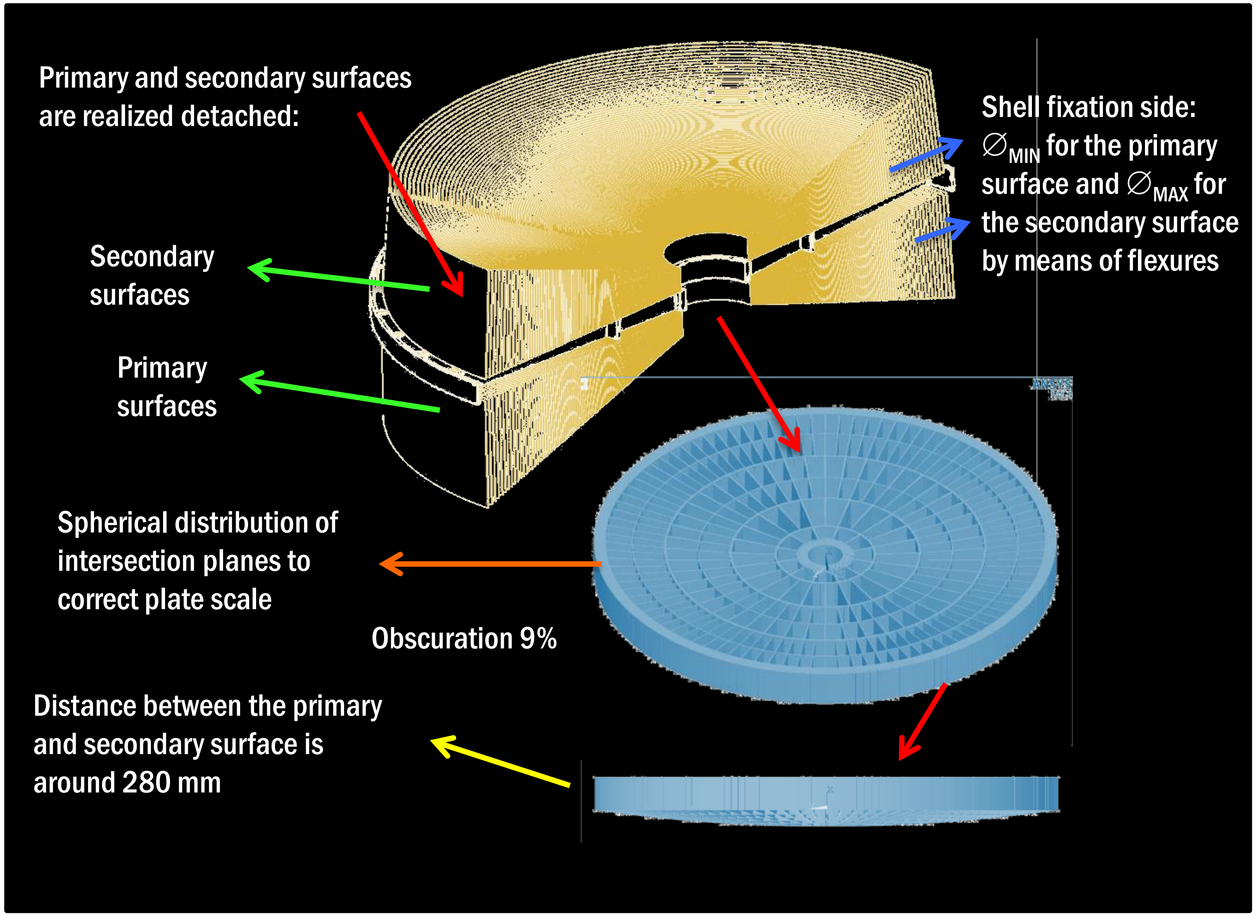
Direct Polished Fused Silica or Similar





Parameters	Values
Gap @ IP (mm)	280
Shift IP (*) (mm)	2.3 (Inner) – 124.7 (Outer)
Total Number of Shells	164 (x2 Primary + Secondary)
Radius (mm)	203.2 (Inner) – 1483.8 (Outer)
SemiShell height IP (mm)	157.9 (Inner) - 348.2 (Outer)
Thickness IP Inner/Outer (mm)	1.6 – 3.4
Total mirror assembly mass (kg)	1,890.7 986.3 Primary 904.4 Secondary
Mirror support structures & thermal control (*estimate*) (kg)	300 (TBC)

Full Shell Process



Process Step

Procurement of fused silica shell

Annealing

Chemical etching

Mounting the shell in a Shell Supporting System

Fine grinding

Bonnet polishing

Pitch polishing

Ion beam figuring

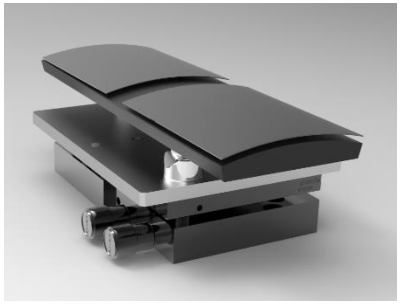
Coating

X-ray calibration

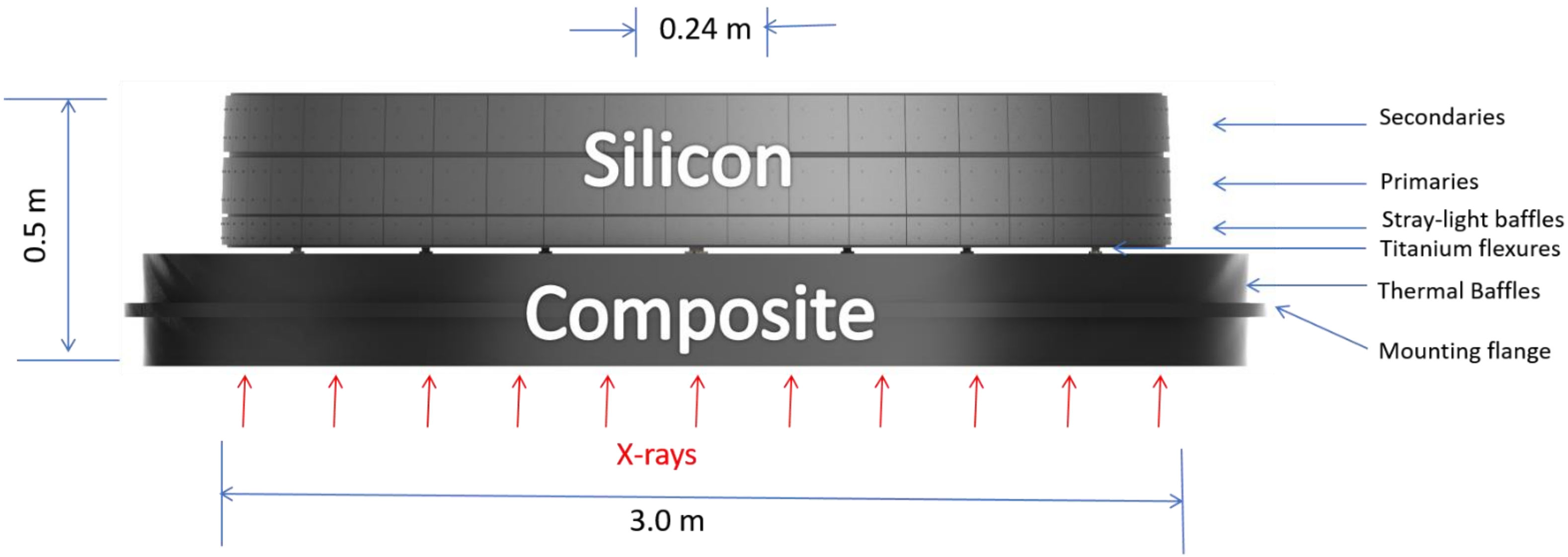
Silicon Meta-Shell Optics (SMO)

- W.W. Zhang & NGXO Team (NASA GSFC)

Direct polished mono-crystalline silicon

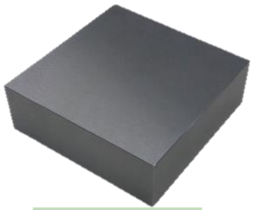


Parameters	Values
Total Number of Segments	37,492
Total Number of Meta-Shells	12
Radius (mm)	120 (Inner) – 1500 (Outer)
Segment Size (L x H) (mm)	100 x 100
Thickness Inner/Outer (mm)	0.5
Total mirror assembly mass (kg)	1,185 (including straylight & thermal baffles + structures)



Silicon Meta-Shell Optics Process

Mirror Fabrication



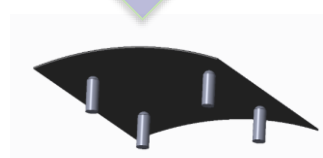
Polishing and light-weighting of single crystal silicon to achieve best possible PSF

Coating

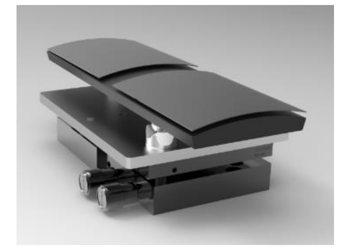
Precision cancellation of iridium stress with silicon oxide stress to achieve distortion-free coating

Alignment & Bonding

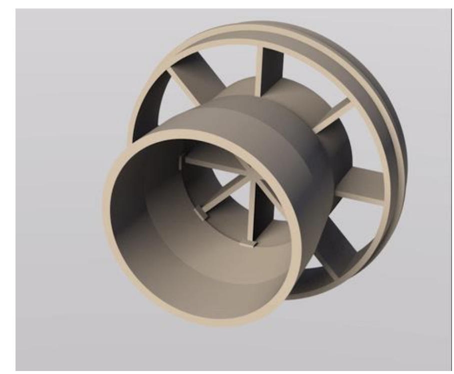
Kinematic 4-point support for alignment and epoxy bonding to minimize gravity release error



Process Validation



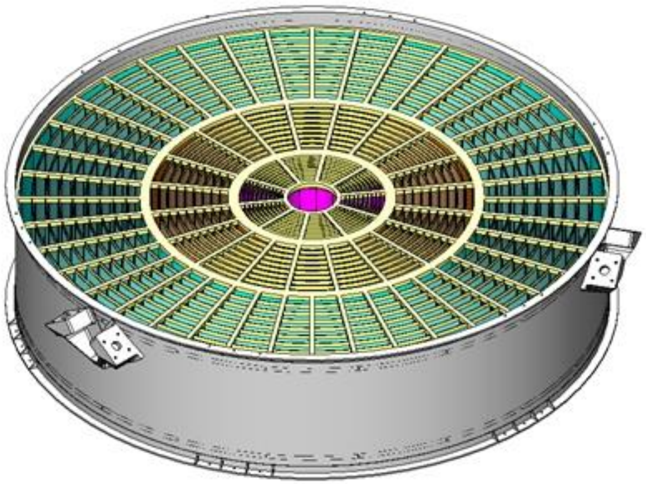
Building-up of a meta-shell

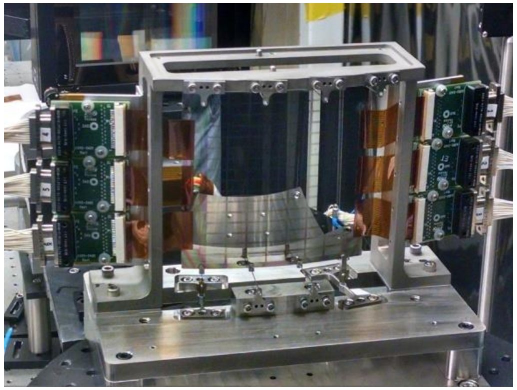


Adjustable Optics

- P. Reid
- SAO Adjustable Optics Team
- PSU Adjustable Optics Team

Slumped glass with sputter deposited piezoelectric material

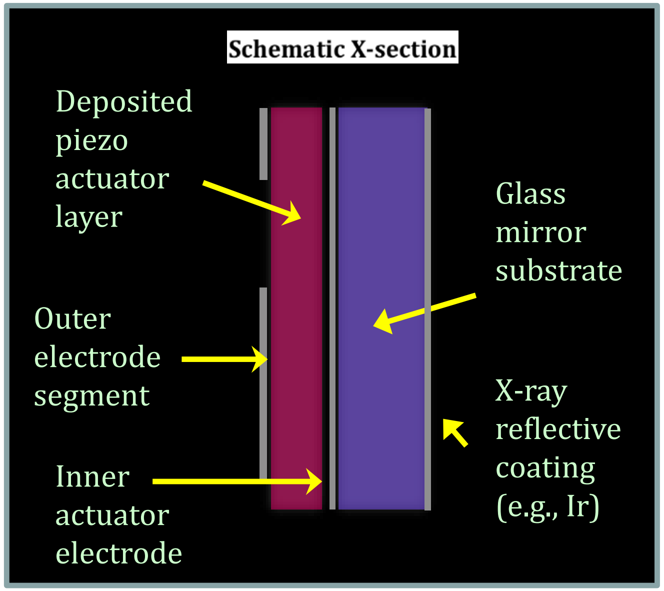


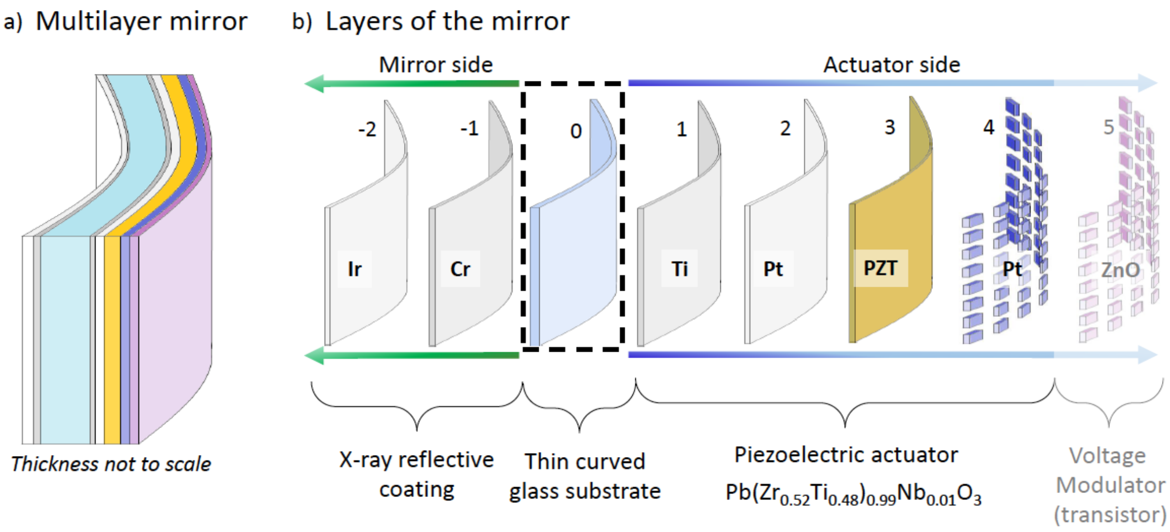


Parameters	Values
Total Number of Segments	12,720
Total Number of Shells	265
Number of Piezoelectric adjuster cells per mirror segment	~1500
Number of strain gauges per segment	~2000*
Radius (mm)	200 (Inner) – 1500 (Outer)
Segment Size (L x H) (mm)	200 x 220 – 200 x 120
Thickness Inner/Outer (mm)	0.4
Total mirror assembly mass (kg)	1,580 (includes pre- and post- thermal collimators)

* New analysis (post-evaluation) reduces 2000 strain gauges per segment to 10 per segment, and is an optional feature.

Adjustable Optics Process

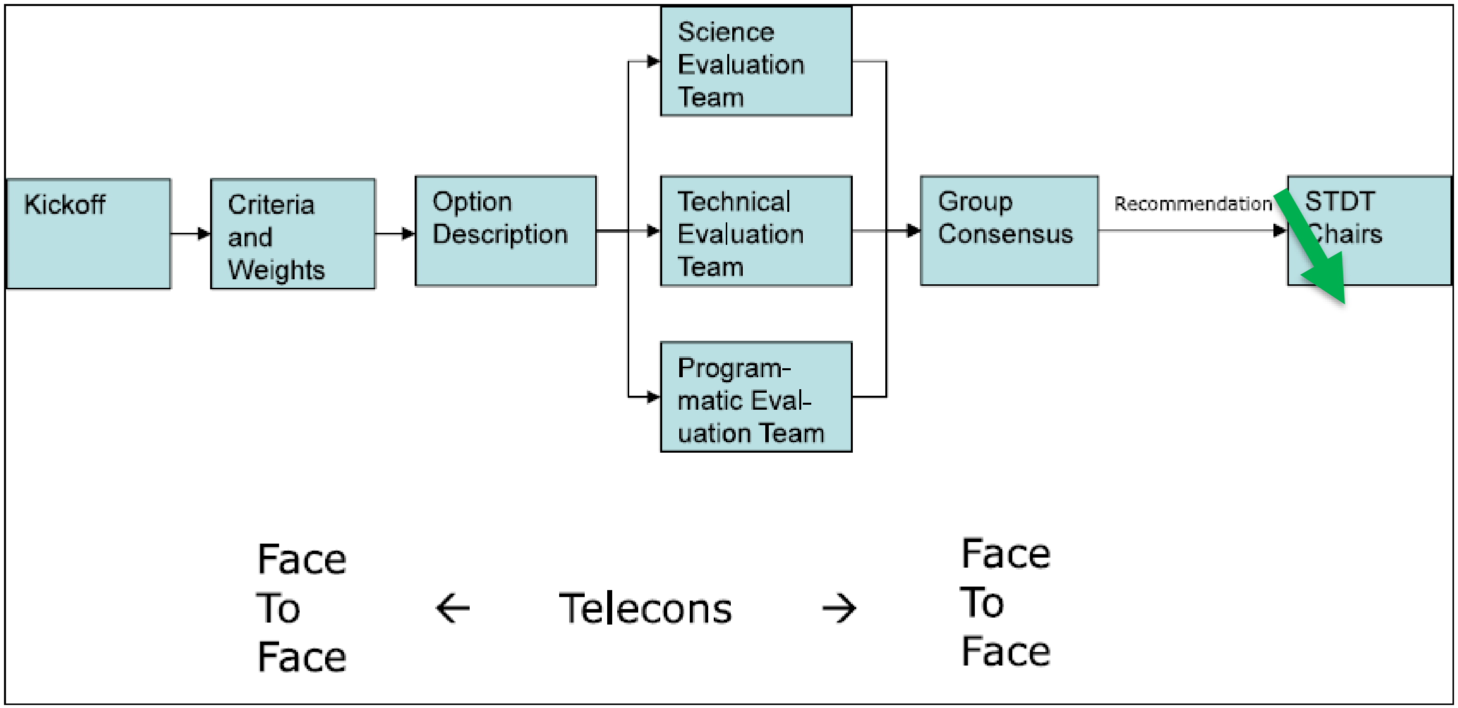




Gary Blackwood, NASA JPL
Exoplanet Program Office

TRADE RESULTS

LMAT Working Group - Work Flow



Final Trade Matrix

- Consensus reached on all Musts, Wants, Risks and Opportunities in 20 hours of LMAT clock time
- One Want was not in consensus (see dissenting opinion)
- Only Key Wants (78 points of 100) were scored in weighted sum
- Effect of non-Key Wants and Dissent did not change Final Recommendation
- <u>Final Consensus Recommendation:</u> (accounting for Risks and Opportunities): **Silicon Meta Shell** as DRM concept, Adjustable and Full Shell as feasible alternates

DECISION STATEMENT: Recommend **one DRM concept** Mirror Optical Assembly Architecture to **focus the design** for the final report and identify any **feasible alternates**

Risk Evaluation

						Adjustable		Full Shell		Silicon Meta Shell
MUSTS										
	Science	Per defn / analysis of SET								
M1	Optical performance will meet reqts flowing down from Science Trace Matrix					Y		Y		Y
	Technical	Per defn / analysis of TET								
M2	Credible roadmap from today's status to predict flight on-orbit performance					Y		Y		Y
M3	Performance modeling tools related to current results are demonstrated to be credible					Y		Y		Y
M4	Repeatable fabrication process based on current status					Y		Y		Y
M5	Credible error budget that flows down to each mirror element					Y		Y		Y
M6	Expected to survive launch					Y		Y		Y
	Programmatic	Per defn / analysis of PET								
M7	Show a credible plan to meet TRL 4-6					Y		Y		Y
M8	Produce the mirror assembly within the Program schedule allocation					Y		Y		Y
WANTS		***Key***	***Driving***	***Weights***						
	Technical	Per defn / analysis of TET			*Score*		*Score*		*Score*	
W1	Highest predicted technology readiness at Astro2020 by March 2020	K	D	12	7	small-significant	7	small-significant	10	Small difference
W2	Relative demonstrated performance	K	D	12	4	**SIG./VL DIFFERENCE**	4	**SIG./VL DIFFERENCE**	10	BEST
W3	Relative credibility of roadmaps from today's status to predict flight on-orbit performance (reflects M2)	K	D	12	5	SIG. DIFFERENCE	5	SIG. DIFFERENCE	10	BEST
W4	Relative simplicity of mirror assembly production process and test	K		10	8	small difference	10	BEST	10	BEST
W5	Relative contamination control (cost, complexity)			1		DIFFERENCE		BEST		DIFFERENCE
W6	Relative ease of implementing stray light control			3		DIFFERENCE		BEST		DIFFERENCE
W7	Relative ease of implementing thermal control and baffling			4		DIFFERENCE		BEST		BEST
W8	Relative ease of creating a system option for charged particle mitigation			1		*WASH*		*WASH*		*WASH*
W10	Relative confidence in launch survivability (reflects M6)			3		*WASH*		*WASH*		*WASH*
W11	Relative complexity and accuracy of ground calibration of mirror assembly	K		6	8	small difference	10	BEST	10	BEST
W13	Relative impact of technical accommodation (cost, mass, spacecraft resources, etc...)	K	D	10	8	small difference	5	SIG. DIFFERENCE	10	BEST
	Subtotal					**400**		**402**		**620**
	Programmatic	Per defn / analysis of PET								
W12	Relative cost and credibility of grass-roots cost estimate of the mirror assembly through delivery	K		10	10	*WASH*	10	*WASH*	10	*WASH*
W14	Lowest relative cost to reach TRL5 and 6			3		*WASH*		*WASH*		*WASH*
W16	Best assessment of the cost of ground calibration of mirror assembly			3		DIFFERENCE		BEST		BEST
W17	Earliest date to reach TRL5 and 6			4		DIFFERENCE		BEST		DIFFERENCE
W18	Best assessment of the schedule to mirror assembly delivery (reflects M8)	K		6	8	small difference	10	BEST	8	small difference
	Subtotal					**148**		**160**		**148**
	Total			100	**548**		**562**		**768**	
RISKS	*See wording for each in TET package*			PET Ref#		**C, L**		**C, L**		**C, L**
R1	Credible Roadmap (WRT M2)					3, 3		3, 2		3, 2
R2	Repeatable correct fabrication					5, 1		5, 1		5, 1
R3-5	Credible Error Budget					5, 1		3, 1		3, 2
R6	Launch Survival (risk of running out of design space to meet margin)					3, 1		3, 1		3, 1
R7	Programmatic impact of Low Mirror yield IF the process yield is less than expected then it will			R1		3, 3		4,3		4,2
R8	Mirror Technology Maturation (only risk related to M7)			R2		3, 4		3, 4		3,2
R9	Industry Engagement (lack of insufficient)			R3		4, 2		4, 1		4, 3
R10	Efficiency of Mirror Alignment and Bonding (no eval for full shell)			R4		3, 2				3, 4
R11	Difference in Execution of Repetitive Activities (including metrology environment)			R5		2, 3		1,3		3, 1
R12	Mirror Shell delivery by Corning			R6		n/a		4, 2		n/a
R13	Adhesive Cure Time			R7						3, 2
R14	Risk of observatory mass exceeding LV requrements If the mirror assembly mass increases beyond 2600kg (includes MGA)					4,1		4,3		4, 1
R15	Meeting 1.2 arc seconds: If cannot meet 1.2 arc seconds due to =>					5,2		5,2		5,2
OPPORTUNITIES	*See wording for each in TET package*			PET Ref#		**B, L**		**B, L**		**B, L**
O1	Coatings					4, 4		4, 4		4, 4
O2	Adjustability to help meet requirements before and after launch									
O3	ESA and ASI Partnership (Full Shell)			O1						
O5	If the mirror assembly can be redesigned (while meeting all other requirements) to improve grasp at					3,4		3,4		3,5

Results (Musts)

DECISION STATEMENT: Recommend one DRM concept Mirror Optical Assembly Architecture to focus the design for the final report and identify any feasible alternates					
			Adjustable	**Full Shell**	**Silicon Meta Shell**
MUSTS					
	Science	Per defn / analysis of SET			
M1	Optical performance will meet reqts flowing down from Science Trace Matrix		Y	Y	Y
	Technical	Per defn / analysis of TET			
M2	Credible roadmap from today's status to predict flight on-orbit performance		Y	Y	Y
M3	Performance modeling tools related to current results are demonstrated to be credible		Y	Y	Y
M4	Repeatable fabrication process based on current status		Y	Y	Y
M5	Credible error budget that flows down to each mirror element		Y	Y	Y
M6	Expected to survive launch		Y	Y	Y
	Programmatic	Per defn / analysis of PET			
M7	Show a credible plan to meet TRL 4-6		Y	Y	Y
M8	Produce the mirror assembly within the Program schedule allocation		Y	Y	Y

- All 3 architectures passed the “Musts”.
- One note related to the Science criteria is that the full-shell optical design used for this study requires additional integration time for some observations. This was deemed by the LMAT to have minor consequence and can be mitigated.

Frits Paerels, Columbia University (SET Chair, Presenter)

Ryan Hickox, Dartmouth College

Daniel Stern, NASA JPL

SCIENCE EVALUATION TEAM – SCIENCE ‘MUSTS’

Scientific Evaluation

LMAT *Must* 1: *Optical performance will meet requirements flowing down from Science Traceability Matrix*

Criteria:

On-axis effective area at 1, 6-8 keV

(BH seed survey sensitivity; SNR at Fe peak)

(bandpass)

Angular resolution

contrast and localization of BH seeds

faint point sources in extended objects (nearby galaxies)

detailed imaging of feedback phenomena

Field of view

imaging of halos of nearby massive galaxies

Grasp: ***off-axis imaging quality***

survey speed (BH seed survey)

Scientific Evaluation

Criteria:

On-axis effective area at 1, 6-8 keV

2 m^2 at 1 keV; 0.1 m^2 at 6-8 keV

(bandpass)

Angular resolution

0.5 arcsec HPD on axis; < 1 arcsec HPD across FOV

Field of view

>10 arcmin with HPD < 1 arcsec

Grasp: ***off-axis imaging quality***

600 $m^2 arcmin^2$ at 1 keV;

more generally: BH Seed Survey no more than 25% of available exposure time in nominal 5 yr mission

Scientific Evaluation

Adjustable Optics	Full Shell Optics	Silicon Metashell Optics
✓	✓	✓

Notes:

1. Off-axis imaging quality can still be optimized (vary focal ratio, mirror length, …): SMO has grasp margin, AO and FSO meet requirements marginally (but within the 'general' formulation of the grasp requirement)

2. Scientific opportunities mostly associated with FOV; not used for evaluation because AO, FSO architectures had not been fully optimized for FOV at 1 arcsec HPD

All Wants

DECISION STATEMENT: Recommend **one DRM concept** Mirror Optical Assembly Architecture to **focus the design** for the final report and identify any **feasible alternates**

					Adjustable		**Full Shell**		**Silicon Meta Shell**	
WANTS		***Ke***	***Driv***	***Weight***						
	Technical	Per defn / analysis of TET			*Score*		*Score*		*Score*	
W1	Highest predicted technology readiness at Astro2020 by March 2020	K	D	12	7	small-significant	7	small-significant	10	Small difference
W2	Relative demonstrated performance	K	D	12	4	**SIG./VL DIFFERENCE**	4	**SIG./VL DIFFERENCE**	10	BEST
W3	Relative credibility of roadmaps from today's status to predict flight on-orbit performance (reflects M2)	K	D	12	5	SIG. DIFFERENCE	5	SIG. DIFFERENCE	10	BEST
W4	Relative simplicity of mirror assembly production process and test	K		10	8	small difference	10	BEST	10	BEST
W5	Relative contamination control (cost, complexity)			1		DIFFERENCE		BEST		DIFFERENCE
W6	Relative ease of implementing stray light control			3		DIFFERENCE		BEST		DIFFERENCE
W7	Relative ease of implementing thermal control and baffling			4		DIFFERENCE		BEST		BEST
W8	Relative ease of creating a system option for charged particle mitigation			1		*WASH*		*WASH*		*WASH*
W10	Relative confidence in launch survivability (reflects M6)			3		*WASH*		*WASH*		*WASH*
W11	Relative complexity and accuracy of ground calibration of mirror assembly	K		6	8	small difference	10	BEST	10	BEST
W13	Relative impact of technical accommodation (cost, mass, spacecraft resources, etc...)	K	D	10	8	small difference	5	SIG. DIFFERENCE	10	BEST
	Subtotal					**400**		**402**		**620**
	Programmatic	Per defn / analysis of PET								
W12	Relative cost and credibility of grass-roots cost estimate of the mirror assembly through delivery	K		10	10	*WASH*	10	*WASH*	10	*WASH*
W14	Lowest relative cost to reach TRL5 and 6			3		*WASH*		*WASH*		*WASH*
W16	Best assessment of the cost of ground calibration of mirror assembly			3		DIFFERENCE		BEST		BEST
W17	Earliest date to reach TRL5 and 6			4		DIFFERENCE		BEST		DIFFERENCE
W18	Best assessment of the schedule to mirror assembly delivery (reflects M8)	K		6	8	small difference	10	BEST	8	small difference
	Subtotal					**148**		**160**		**148**
	Total			100	**548**		**562**		**768**	

subtotal

subtotal

Weighted sum

Weighted Score of Key Wants

- Out of 780 possible points.

DECISION STATEMENT: Recommend **one DRM concept** Mirror Optical Assembly Architecture to **focus the design** for the final report and identify any **feasible alternates**

					Adjustable		Full Shell		Silicon Meta Shell	
	WANTS	***Key***	***Driving***	***Weight***						
	Technical	Per defn / analysis of TET			*Score*		*Score*		*Score*	
W1	Highest predicted technology readiness at Astro2020 by March 2020	K	D	12	7	small-significant	7	small-significant	10	Small difference
W2	Relative demonstrated performance	K	D	12	4	**SIG./VL DIFFERENCE**	4	**SIG./VL DIFFERENCE**	10	BEST
W3	Relative credibility of roadmaps from today's status to predict flight on-orbit performance (reflects M2)	K	D	12	5	SIG. DIFFERENCE	5	SIG. DIFFERENCE	10	BEST
W4	Relative simplicity of mirror assembly production process and test	K		10	8	small difference	10	BEST	10	BEST
W11	Relative complexity and accuracy of ground calibration of mirror assembly	K		6	8	small difference	10	BEST	10	BEST
W13	Relative impact of technical accommodation (cost, mass, spacecraft resources, etc...)	K	D	10	8	small difference	5	SIG. DIFFERENCE	10	BEST
	Subtotal					**400**		**402**		**620**
	Programmatic	Per defn / analysis of PET								
W12	Relative cost and credibility of grass-roots cost estimate of the mirror assembly through delivery	K		10	10	***WASH***	10	***WASH***	10	***WASH***
W18	Best assessment of the schedule to mirror assembly delivery (reflects M8)	K		6	8	small difference	10	BEST	8	small difference
	Subtotal					**148**		**160**		**148**
	Total			100	**548**		**562**		**768**	

W4, W11, W12, W18 were Key but not Driving

W3 was Dissented – see detail following pages

Gabe Karpati, NASA GSFC, (TET Chair)
Jon Arenberg , NGAS
David Broadway, NASA MSFC
Marta Civitani, OAB
Lester Cohen, Harvard SAO
Mark Freeman, Harvard SAO

Paul Glenn, Bauer Associates, Inc.
Gary Mathews, ATA Aerospace LLC
Ryan McClelland, NASA GSFC
Ted Mooney, Harris
Mark Schattenburg, MIT
Dave Windt, Reflective X-ray Optics LLC

TECHNICAL EVALUATION TEAM – KEY 'WANTS'

W1 – Predicted Technology Readiness in 2020

					Adjustable		Full Shell		Silicon Meta Shell	
W1	Highest predicted technology readiness at Astro2020 by March 2020	K	D	12	7	small-significant	7	small-significant	10	BEST

- The three mirror and Lynx Mirror Assembly (LMA) concepts were assessed based on the information provided by the teams and the tailored NASA TRL level (see appendix)
- An independent assessment based on the TRL parameters provided by NASA was also conducted.
- Emphasis on relative ranking for trade, not formal absolute TRL evaluation

Consensus

Basis (did not attempt consensus)

	Adjustable	Full Shell	SMO
Current Claimed TRL (Assessed by Advocates)	Mirror TRL 3 LMA TRL 2	Mirror TRL 2 LMA TRL TBD	Mirror TRL 4 LMA TRL 4
Current Assessed TRL (Assessed by the TET)	Mirror TRL ~2 LMA TRL ~TBD	Mirror TRL ~2 LMA TRL ~2	Mirror TRL ~4 LMA TRL ~4
Proposed 2020 TRL (Assessed by the TET)	Mirror TRL 4 LMA TRL TBD	Mirror LMA TRL 4	Mirror TRL 5 LMA TRL 5

W2 – Relative Demonstrated Performance

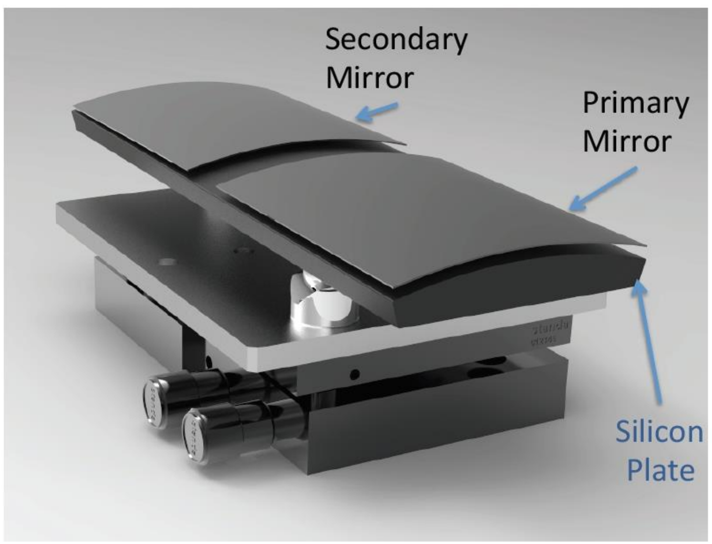
					Adjustable		Full Shell		Silicon Meta Shell	
W2	Relative demonstrated performance	K	D	12	4	SIGN./VL	4	SIGN./VL	10	BEST

Performance Element	Adjustable	Full Shell	SMO
Key Challenges	Utilization of mirror replication and implementation of active technology, assembly of the many small mirror segments, high quantity fabrication and assembly of small segments	Large, thin shell fabrication, large thin shell assembly, handling during integration and predictable yields	Assembly of the many small mirror segments, stability of a passive, segmented mirror assembly, high quantity fabrication and assembly of small segments
Fabrication	While an initial active sample has been fabricated to evaluate initial correctability, it does not address many of the key challenges associated with the adjustable optics approach.	Significant risks as compared to the segmented approaches, but the quantity of mirrors is much less.	The initial processing and ion figuring on a sample mirror segment shows convergence.
Assembly	Bonding and mounting process TBD. The segment to segment alignment and stability is a risk that still must be fully demonstrated.	The significantly fewer number of optical components that need to be assembled will help the full shell approach. Incomplete Key demonstrations to show feasibility of assembly.	The ability to achieve the precision spacing required for the segment-segment alignment in a reasonable cost/ schedule needs to be demonstrated early in the concept development.
Assessment	Use of replication, and low TRL corrective approach combined with high volume production and assembly make this less demonstrated performance than SMO.	Demonstrated fabrication is a key gap. Less demonstrated imaging performance than SMO.	Best demonstrated performance to date, significant key early demonstrations remain,

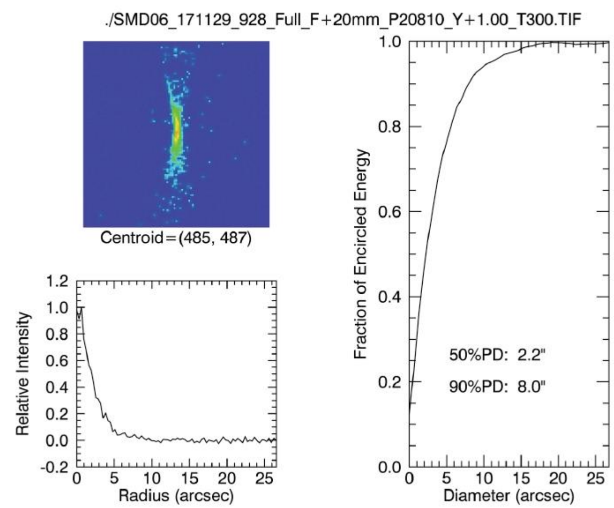
W2 – Relative Demonstrated Performance

					Adjustable		Full Shell		Silicon Meta Shell	
W2	Relative demonstrated performance	K	D	12	4	SIGN./VL	4	SIGN./VL	10	BEST

Performance Element	Adjustable	Full Shell	SMO
Testing to Date	No mirrors have been fabricated to date but a brass board has been completed that demonstrates the overall theory of the concept of correction. No x-ray testing to date.	Two mirror fabricated to date. Both mirrors were damaged prior to completion. The best mirror was 17 arcsec HPD (X-ray Test) prior to the damage.	The Silicon Meta-Shell process has fabricated 60 mirrors in the ~3 arcsec to 5 arcsec range (X-ray Test) using traditional processing techniques. Best performance 2.2 arcsec



Two uncoated mono-crystalline silicon mirrors aligned and bonded on a silicon platform



Full illumination with Ti-K X-rays (4.5 keV)

Effective Area at Ti-K (cm^2): 0.266 predicted, 0.260 measured, 2.3% deficit.

Acknowledgement: Thanks to Vadim Burwitz and his team at Panther who performed this measurement.

W3 – Relative Credibility of Roadmaps

					Adjustable		Full Shell		Silicon Meta Shell	
W3	Relative credibility of roadmaps from today's status to predict flight on-orbit performance (reflected M2)	K	D	12	5	SIGN. DIFFERENCE	5	SIGN. DIFFERENCE	10	BEST

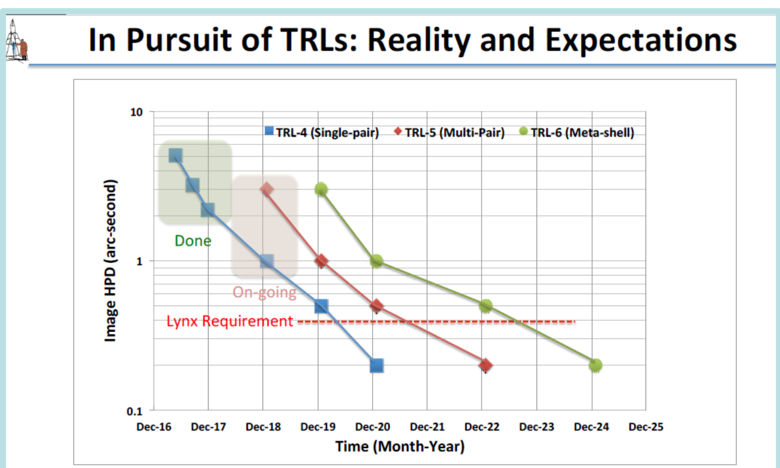
Roadmap definition detail

- Steps
- Success criteria defined & Quality of these criteria
- Likelihood of success of each step
    - Analysis
    - Previous demonstration
    - Track record
    - Engineering judgement

		Adjustable	Full Shell	SMO
Submitted material	Roadmap	21 pages	VG Package	Three VG packages
Submitted material	Supporting Material	References cited	9 files	N/A
Steps defined		76 (19x4)	TRL 2/3, 4, 5, (6)	TRL-4,5,6 Demos and Tech Challenges
# of Steps to go		76-35=41	TRL 2/3, 4, 5, (6)	TRL-4,5,6
Success criteria defined		Yes, 15 of 19 quantitative	Implied	Yes
Likelihood of success		Acceptable with proper resources	Acceptable with proper resources	Acceptable with proper resources

W3 – Relative Credibility of Roadmaps

Criteria		Adjustable	Full Shell	SMO
Detail	Specificity	Best	Good on backup and justification materials	**Good, good history of progress**
	Criteria	Best	Least (but there)	**Middle**
	Pr(S)	Lowest/not highest	Middle/not highest	**Highest**
Length of Road		Longest	Middle	**Shortest**



Assessment

- Silicon Meta-Shell Optics (SMO) was assessed to have the most credible roadmap.
- Roadmaps for LMAT are NOT the same creatures as roadmaps for Lynx development
  - Not even the best of these roadmaps, or even the concatenated best bits from all is ready for prime time
- Lots of work ahead

Dissenting Opinion on Want 3

					Adjustable		Full Shell		Silicon Meta Shell	
W3	Relative credibility of roadmaps from today's status to predict flight on-orbit performance (reflected M2)	K	D	12	5	SIGN. DIFFERENCE	5	SIGN. DIFFERENCE	10	BEST

- All parties agreed with evaluation of Full Shell and Silicon Meta Shell
- Some LMAT members were in Consensus Category 2 – disagree but willing to fully support the decision
- All parties were in Consensus Category 1 or 2 for Adjustable except for two members of LMAT
- Per the NASA Process for Dissenting Opinion, the dissent is recorded on the following page.

Dissenting Opinion for Want 3

Paul Reid and Eric Schwartz, speaking as LMAT Members:

We dissent from the ranking and scoring of Want 3. We believe the Adjustable Optics response should have been scored at minimum tied for "Best," if not the outright "Best."

> The TET report stated*: "For this attribute of Want 3 the **AO <Adjustable Optics>** submission <roadmap> was found to be the most detailed, followed by **full shell** and **silicon meta-shell**." and "The TET considered the current state of technology, the starting point and the completeness of the path ahead to rank this attribute. "*

- Past and near term performance of SMO is acknowledged as best. Highly weighted in W1 and W2.
- The technical roadmap needs to be forward-looking.
- Difficult challenges ahead for all three technologies.
- This is an opportunity for a critical evaluation of technical challenges ahead, which we believe were largely unexamined in this analysis.

W13 – Relative Required Observatory Technical Accommodation

					Adjustable		Full Shell		Silicon Meta Shell	
W13	Relative impact of technical accommodation (cost, mass, spacecraft resources, etc...)	K	D	10	8	small difference	5	SIGN. DIFFERENCE	10	BEST

- Adjustable: Mass of 1415 kg (does not include thermal collimators) and volume of 7.6 m^3 no details for control electronics given
- Full Shell: Highest mass (2340 kg) larger volume (7.5 m^3) power estimate of 1.2kW (thermal analysis in progress)
- Silicon Meta-Shell: Lowest mass (1185 kg) and smallest volume (5.8 m^3) power estimate of 1.2kW and details of thermal channels and scaled analysis

Impact of non-Key Wants

- Judged non-Key (<5 points each); 22 points total (out of 100)
  - Consensus reached on which Options Scored "Best", and whether there was a "Difference" without assessing the magnitude of the difference

Score	Adjustable	Full Shell	Silicon Meta Shell
Key Wants	548	562	768
All Wants (if Diff=7)	714	782	964

					Adjustable		Full Shell		Silicon Meta Shell	
	W…TS	Ke…	Driv…	Weight						
	Technical	Per defn / analysis of TET			*Score*		*Score*		*Score*	
W5	Relative contamination control (cost, complexity)			1		DIFFERENCE		BEST		DIFFERENCE
W6	Relative ease of implementing stray light control			3		DIFFERENCE		BEST		DIFFERENCE
W7	Relative ease of implementing thermal control and baffling			4		DIFFERENCE		BEST		BEST
W8	Relative ease of creating a system option for charged particle mitigation			1		*WASH*		*WASH*		*WASH*
W10	Relative confidence in launch survivability (reflects M6)			3		*WASH*		*WASH*		*WASH*
	Subtotal					**400**		**402**		**620**
	Programmatic	Per defn / analysis of PET								
W14	Lowest relative cost to reach TRL5 and 6			3		*WASH*		*WASH*		*WASH*
W16	Best assessment of the cost of ground calibration of mirror assembly			3		DIFFERENCE		BEST		BEST
W17	Earliest date to reach TRL5 and 6			4		DIFFERENCE		BEST		DIFFERENCE
	Subtotal					**148**		**160**		**148**
	Total			100	**548**		**562**		**768**	

Analysis of Weighted Scores

- Use the Adjective / Numerical Scoring Scale

Score	Adjustable	Full Shell	Silicon Meta Shell
Key Wants	548	562	768
All Wants (if Diff=7)	714	782	964

Numerical Scoring	
Best=Wash	10
Sm Diff	8-9
Sig Diff	5-6
VL Diff	0-3

- Using the Scoring Scale:
  - A weighted score difference <200 would be a net <u>small difference</u>
  - A weighted score difference >400 would be net <u>significant difference</u>

- Analyzing both the Key and All Wants:
  - There is no meaningful difference between Adjustable and Full Shell
  - There is at least a small difference which favors Silicon Meta Shell, but not one that is significant

Risk Analysis – Kepner-Tregoe

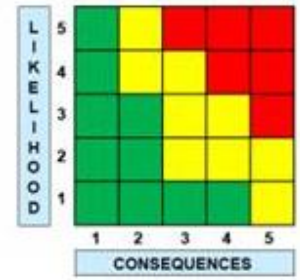
Risks identified during the LMAT study pertain mainly to the requested trade material, and are scored on a relative scale (relative to the technologies being traded). These Kepner-Tregoe risks do not necessarily reflect absolute risks to the technologies. All technology risks will be identified and presented in the Lynx Final Report.

Assume
- $1B for Allocated cost
- 25% of that through PDR

SET, TET and PET will recommend (to LMAT) the C, L for their risks

<u>Opportunity Cube: </u>Same Likelihood; Benefits are Consequences with opposite sign

Likelihood	Safety Estimated likelihood of Safety event occurrence	Technical Estimated likelihood of not meeting performance requirements	Cost Schedule Estimated likelihood of not meeting cost or schedule commitment
5 Very High	$(P_{SE} > 10^{-1})$	$(P_T > 50\%)$	$(P_{CS} > 75\%)$
4 High	$(10^{-2} < P_{SE} \leq 10^{-1})$	$(25\% < P_T \leq 50\%)$	$(50\% < P_{CS} \leq 75\%)$
3 Moderate	$(10^{-3} < P_{SE} \leq 10^{-2})$	$(15\% < P_T \leq 25\%)$	$(25\% < P_{CS} \leq 50\%)$
2 Low	$(10^{-5} < P_{SE} \leq 10^{-3})$	$(2\% < P_T \leq 15\%)$	$(10\% < P_{CS} \leq 25\%)$
1 Very Low	$(10^{-6} < P_{SE} \leq 10^{-5})$	$(0.1\% < P_T \leq 2\%)$	$(2\% < P_{CS} \leq 10\%)$



Consequence Categories					
Risk	1 Very Low	2 Low	3 Moderate	4 High	5 Very High
Safety	Negligible or not impact	Could cause the need for only minor first aid treatment	May cause minor injury or occupational illness or minor property damage	May cause severe injury or occupational illness or major property damage.	May cause death or permanently disabling injury or destruction of property.
Technical	No impact to full mission success criteria	Minor impact to full mission success criteria	Moderate impact to full mission success criteria. Minimum mission success criteria is achievable with margin	Major impact to full mission success criteria. Minimum mission success criteria is achievable	Minimum mission success criteria is not achievable
Schedule	Negligible or no schedule impact	Minor impact to schedule milestones; accommodates within reserves; no impact to critical path	Impact to schedule milestones; accommodates within reserves; moderate impact to critical path	Major impact to schedule milestones; major impact to critical path	Cannot meet schedule and program milestones
Cost	<2% increase over allocated and negligible impact on reserve	Between 2% and 5% increase over allocated and can handle with reserve	Between 5% and 7% increase over allocated and cannot handle with reserve	Between 7% and 10% increase over allocated, and/or exceeds proper reserves	>10% increase over allocated, and/or can't handle with reserves

HIGH RISK

MODERATE RISK

LOW RISK

Figure 3, GSFC Risk Matrix Standard Scale

Risk Analysis

- Consensus reached relative risk rankings
- Risk evaluation did not cause the LMAT to change recommendation from the highest-scoring option (Silicon Meta Shell)
- Three risks were noted for relative Consequence, Likelihood

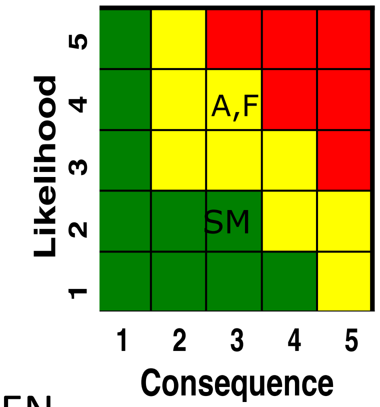
			Adjustable	Full Shell	Silicon Meta Shell
RISKS	*See wording for each in TET package*	PET Ref#	**C, L**	**C, L**	**C, L**
R1	Credible Roadmap (WRT M2)		3, 3	3, 2	3, 2
R2	Repeatable correct fabrication		5, 1	5, 1	5, 1
R3-5	Credible Error Budget		5, 1	3, 1	3, 2
R6	Launch Survival (risk of running out of design space to meet margin)		3, 1	3, 1	3, 1
R7	Programmatic impact of Low Mirror yield IF the process yield is less than expected then it	R1	3, 3	4,3	4,2
R8	Mirror Technology Maturation (only risk related to M7)	R2	3, 4	3, 4	3,2
R9	Industry Engagement (lack of insufficient)	R3	4, 2	4, 1	4, 3
R10	Efficiency of Mirror Alignment and Bonding (no eval for full shell)	R4	3, 2		3, 4
R11	Difference in Execution of Repetitive Activities (including metrology environment)	R5	2, 3	1,3	3, 1
R12	Mirror Shell delivery by Corning	R6	n/a	4, 2	n/a
R13	Adhesive Cure Time	R7			3, 2
R14	Risk of observatory mass exceeding LV requrements If the mirror assembly mass increases beyond 2600kg (includes MGA)		4,1	4,3	4, 1
R15	Meeting 1.2 arc seconds: If cannot meet 1.2 arc seconds due to =>		5,2	5,2	5,2

Jaya Bajpayee, NASA ARC (PET Chair, Presenter)
Charlie Atkinson, Northrop Grumman
Karen Gelmis, NASA MSFC
John Nousek, Penn State University
Bill Purcell, Ball
Steve Jordan, Ball

PROGRAMMATIC EVALUATION TEAM -RISK ASSESSMENT

Risk 2: Mirror Technology Maturation

Adjustable		Full Shell		Silicon Meta Shell	
L	C	L	C	L	C
4	3	4	3	2	3

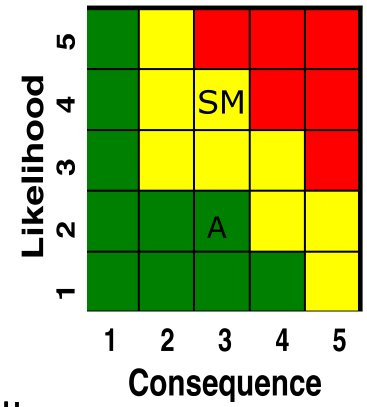


- IF mirror technology maturation does not progress as planned, THEN TRL-6 demonstration will be delayed, delaying the entire program.

Adjustable	Full Shell	Silicon Meta Shell
Adjustable mirror schedule is very well thought out, but has a multitude of steps that have not been proven out and therefore represent a schedule risk to execution per the schedule/plan that has been provided.	Risk to full shell reaching TRL-5 and -6 because only 17 arcsec has been demonstrated to date and mirror breakage.	Performance improvement expected in processes applied to silicon wafer may not be accomplished

Risk 4: Efficiency of Mirror Alignment and Bonding
Adjustable and Silicon Meta Shell

Adjustable		Full Shell		Silicon Meta Shell	
L	C	L	C	L	C
2	3			4	3

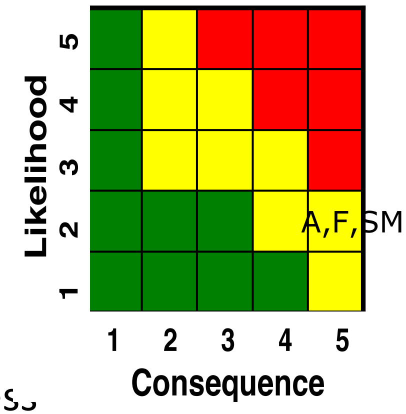


- IF installation and alignment of individual mirrors and/or groups of mirrors is not an efficient proven repeatable process, THEN there will be significant schedule (and associated cost) growth.

Adjustable	Full Shell	Silicon Meta Shell
We have a concern regarding their ability to align the mirrors in a production manner that closes around an achievable schedule. For the mirror manufacturing itself, parallel manufacturing lines allow the schedule to be compressed, however assembly of the LMA is inherently a sequential process.		We have a concern regarding their ability to align the mirrors in a production manner that closes around an achievable schedule. For the mirror manufacturing itself, parallel manufacturing lines allow the schedule to be compressed, however assembly of the LMA is inherently a sequential process. Mirror alignment requirement is significantly tighter than Adjustable.

Risk 15: Meeting 1.2 arcseconds

Adjustable		Full Shell		Silicon Meta Shell	
L	C	L	C	L	C
2	5	2	5	2	5



- If we don't meet 1.2 arc seconds due to coatings, adhesive and thickness long term stability assembly and alignment at TRL (PDR) then there will be a loss of science.

- Same Likelihood and Consequence for all 3 technologies. Highlights the importance of a robust technology maturation plan and continued investment in critical development areas.

Opportunity Analysis

- Consensus Reached on Opportunity Color. Darker Blue is a better Opportunity

DECISION STATEMENT: Recommend **one DRM concept** Mirror Optical Assembly Architecture to **focus the design** for the final report and identify any **feasible alternates**

						Adjustable		Full Shell		Silicon Meta Shell
OPPORTUNITIES	*See wording for each in TET package*			PET Ref#		**B, L**		**B, L**		**B, L**
O1	Coatings					4, 4		4, 4		4, 4
O2	Adjustability to help meet requirements before and after launch									
O3	ESA and ASI Partnership (Full Shell)			O1						
O5	If the mirror assembly can be redesigned (while meeting all other requirements) to improve grasp					3,4		3,4		3,5

- Multiple opportunities were identified for each technology
- These opportunities, although beneficial, did not cause the LMAT to deviate from recommending the highest-scoring option (Silicon Meta-Shell Optics)
- The opportunities identified should be fully assessed and exploited in the final report

Gary Blackwood, NASA JPL
Exoplanet Exploration Program Office

FINAL RECOMMENDATION ACCOUNTING FOR RISKS AND OPPORTUNITIES

LMAT Assessment - Summary

- Report of the LMAT:

<u>Final Consensus Recommendation:</u> The LMAT recommends the Silicon Meta Shell as the DRM concept Mirror Optical Assembly Architecture to focus the design for the Final Report.

Full Shell and Adjustable Optics determined to be feasible alternates.

Jessica Gaskin, NASA MSFC

Lynx Study Scientist

FEASIBILITY

Feasibility

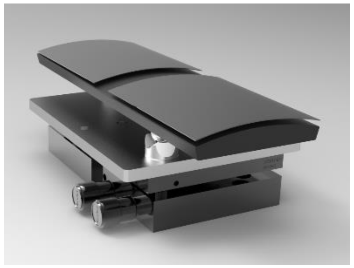
- Plan for all 3 mirror technologies to reach (or approach) TRL 4 by March 2020 is feasible (technically) and credible within existing resources (schedule, cost).

- Using the Matrix Scoring and Risk Assessment, areas that the LMAT recommends further NASA investment include:
  - Alignment and bonding (mounting)
  - Metrology
  - Calibration
  - Predictive modeling (of elements and system)

- Feasibility of all 3 mirror technologies should be reassessed once Lynx has been selected as a Program.

SMO Key Challenges/Tasks for Meeting TRL

Single-Pair Modules (TRL-4)



Objectives:

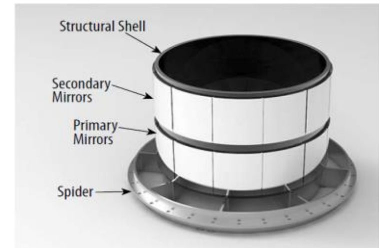
1. Develop and verify mirror fabrication and mirror coating processes.
2. Develop and verify the basic elements of alignment & bonding procedures for precision and accuracy.

Multiple-Pair Modules (TRL-5)

Objectives:

1. Develop and verify mechanics and speed of co-alignment and bonding processes.
2. Conduct environmental tests: vibration, thermal vacuum, and acoustic to verify structural and performance robustness.

Meta-Shells (TRL-6)

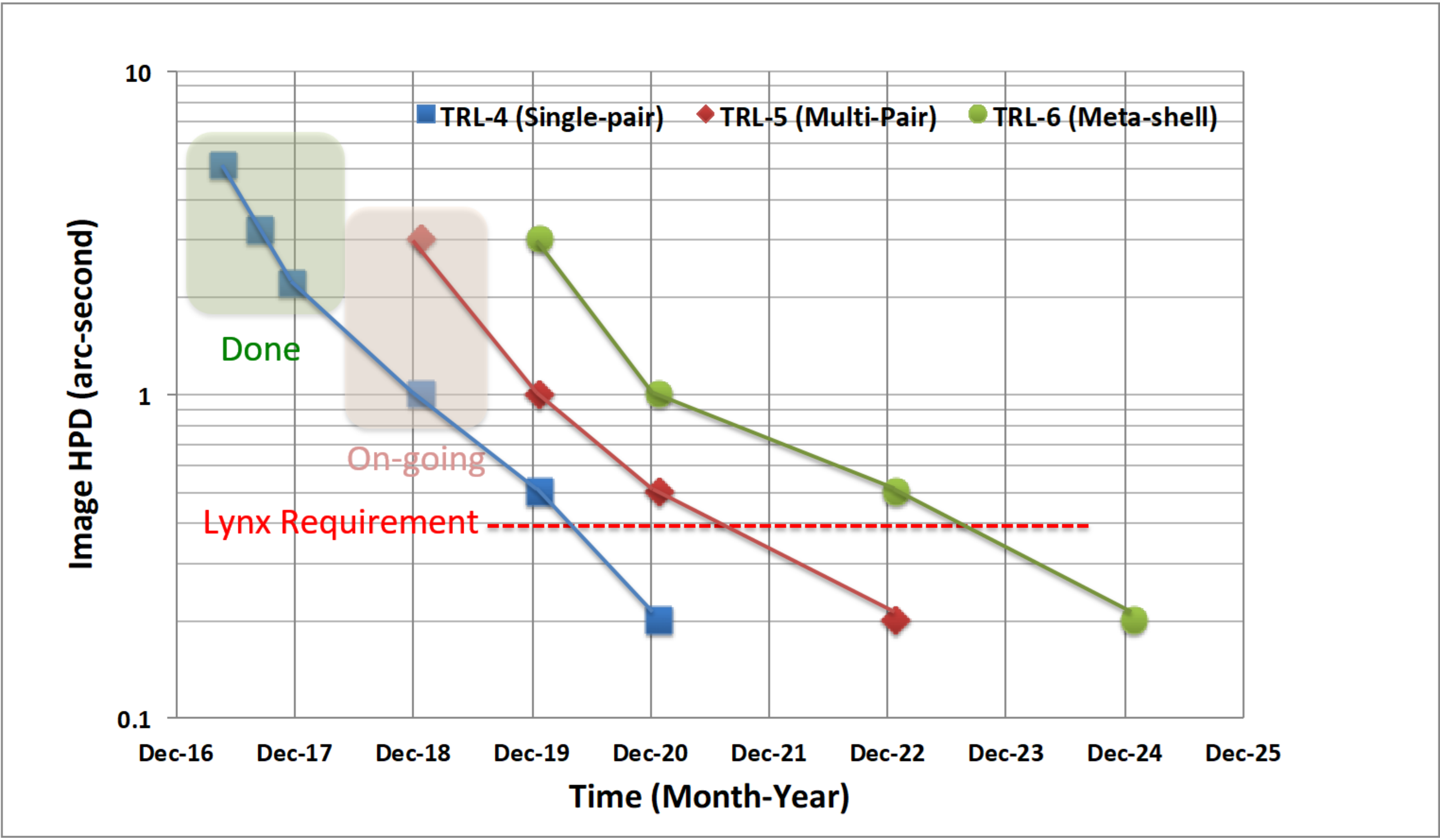


Objectives:

1. Develop and verify all aspects of meta-shell production process: mirror fabrication, coating, alignment, and bonding.
2. Validate production schedule and cost estimates.
3. Develop and plan for mass production.

***TRLs were defined by the LMAT and are in the backup slides of this presentation.**

SMO Goals and Expectations



Strengthening Feasibility for Lynx Decadal Report

The Silicon Meta-Shell Optics is at a relatively high TRL (compared to other technologies at this point in time), and has many advantages that were identified in the Trade Study.

Areas that could be strengthened for SMO in the Lynx Final Report to the Decadal includes:

- Relative Contamination Control
- Implementing Stray Light Control
- Manufacturing (cost and schedule)
- Industry Engagement
- Optimization and clarification of Roadmap Details
- Mirror Alignment and Bonding (& Adhesive Cure Time)
- Calibration Plan
- Error Budget (and Error Uncertainties/Predictive Modeling)

*All feasible mirror architectures to be included in the final report should utilize the Trade Study findings to strengthen their Roadmap and other areas.

Adjustable Optics: Key Technology Gaps to Reach TRL4

Key technology gaps we need to bridge to get to TRL4 – *estimated cost to get the TRL4 is $1.95M, we don't expect that level of funding is available via SAT/APRA grants and internal SAO funding, we will most likely far short of that funding level. We may need additional funding sources to get the TRL4 in the time frame we presented to the LMAT (Q1 2020)*

1) **Mirror post polishing** – develop a method to polish/figure the mirror blank after slumping and the PZTs and associated electronics have been incorporated on the mirror back. MRF polishing is the furthest along, having been tested on two representative parts, but other possible methods could be ion figuring, ion implantation, or differential deposition.
2) **Row/Column addressing on the mirror** – develop the hardware and the methodology to incorporate ZnO transistors directly on the back of each mirror to facilitate row/column addressing, thus simplifying the mirror electronics architecture.
3) **Strain gauges** – while we have drastically cut back on the use of strain gauges by eliminating them for direct mirror figure measurement, we still need a smaller number of strain gauges on each mirror to serve as temperature sensors. This technology needs to be developed and strain gauges need to be tested on our mirrors.
4) **Mounting** – development of a fully light weighted frame mount needs to continue.
5) **Alignment** – development of alignment test methodology and hardware to support the alignment of a single mirror pair.

Adjustable Optics:
Key Technology Gaps to Reach TRL5

Key Technology gaps we need to bridge to get from TRL4 to TRL5 – *estimated cost to get to TRL 5 is $27M, estimated time frame is TRL 5 by Q1 2024.*

1) **Slumping on larger mandrels** – TRL 5 demands full flight-size mirrors (~200mm x 200mm), so we will need to make larger mandrels and be sure the slumping process scales up as expected.
2) **Application of PZTs on a larger substrate** – there is a large investment here, either to acquire a larger deposition chamber at our current partner's (PSU) facility, or to transition to an industry facility that has the capability to sputter PZT material on a larger substrate.
3) **ASIC development** – In a further reduction of the electronic system's complexity, we will distribute mirror control all the way back to individual mirrors via a control ASIC on each mirror. The process and methodology for this hardware and software needs to be developed.
4) **Module development** – TRL5 demands testing of several mirrors in a flight-like module configuration. In a continuation of our frame development, we will need to develop the hardware and methodology to integrate frames into a module assembly, and then build two modules.
5) **Module alignment methodology** – again a continuation of the work we did at TRL4, we will need to extend our mirror pair alignment technique and hardware to facilitate the alignment of many mirror pairs in modules.

Full Shell: Key Technology Gaps

1) The main driver for achieving TRL 4 and TRL 5 for Full-Shell is realizing a fixture capable of supporting and transporting large, thin-shell full-shell optics. This has been designed, but not yet fully implemented due to funding.

2) Fabricating/Polishing thin mirrors to the desired surface with high (predictable) yield (low breakage and repeatable process).

Jessica Gaskin, NASA MSFC
Lynx Study Scientist

NEXT STEPS

Next Steps

Immediate: => Outbriefs

- At the Chairs' discretion, the final briefing package or subset will be communicated to the STDT
  - Was this sufficient? What else do you need?
- The final briefing package or subset will be communicated external to STDT (i.e. NASA HQ)

Medium Term: => Final Report

- Lynx requests that members of the LMAT reassemble prior to final report to review input and roadmaps (continued volunteer basis)
- Advocate teams continue to develop roadmap and material for the Final Report

Long Term: => Technology Development/Maturation and the Decadal

- Advocates continue to work to reach (or approach) TRL 4 by March 2020
- New material/developments presented to Decadal post March 2020
- Continues technology development support from NASA

Key messages:

- All 3 mirror technologies are feasible and viable options
- All 3 mirror technologies are making progress towards maturing their technology
- Large amount of community support

Acknowledgements

NASA JPL – Exoplanet Exploration Program Office

- Gary Blackwood, LMAT Facilitator
- Jennifer Gregory, LMAT Support
- JPL LMAT Support Team (WebEx, Scheduling, ExEP support for travel and time)

LMAT Consensus Group & Host Institutions

- Adjustable Optics Team (SAO, PSU), Full-Shell Optics Team (INAF/OAB, MSFC), Silicon Meta-Shell Optics Team (GSFC),
- Science Evaluation Team (Columbia, NASA JPL, Dartmouth)
- Technical Evaluation Team (NASA GSFC, SAO, ATA Aerospace, Reflective X-ray Optics, INAF/OAB, Bauer Associates, Harris, NGAS, Ball)
- Programmatic Evaluation Team (NASA ARC, Penn State, NASA MSFC, Ball, NGAS)
- Member at Large (MIT)

LMAT Subject Matter Experts, Observers, and Guests & Host Institutions

- NASA HQ, Mindrum, NASA PCOS, MPE, Penn State, U. Iowa, SAO, NASA MSFC)

LMAT Steering Group & Host Institutions

- SAO, Univ. of Arizona, NASA MSFC, NASA GSFC, NGAS, Ball, Harris, NASA ARC, Columbia University, MIT)

- **Special Thanks to NASA HQ for supporting this trade and JPL's involvement**
- **MIT Kavli Institute for hosting the 2nd LMAT Face-To-Face, and for providing a lunch, snacks and coffee**
- **Mindrum for providing a lunch for the 2nd LMAT F2F**

BACKUP

TRL

NASA TRL Definition	*Milestones* for achieving TRLs for the Lynx Mirror Assembly
TRL 3 Analytical studies place the technology in an appropriate context and laboratory demonstrations, modeling and simulation validate analytical prediction.	**Must demonstrate a credible technology development path to the required on-orbit performance of the Lynx Mirror Assembly. Demonstrations must be traceable to the on-orbit performance requirement in the operational environment.** A credible demonstration must comprise the following for these Wolter-Schwarzschild optics: -Realistic end-to-end error budget for Lynx Telescope angular resolution. -Laboratory demonstration of measured angular resolution of mirror elements performing less than a factor of 6 away from their required performance (as stated in the error budget), executed under the following conditions: • Mirror figure, and if applicable the ability to correct mirror figure, for a single mirror segment or for a full shell segment demonstrated via metrology or X-ray testing. • Early proof-of-concept of mirror mounting and all essential hardware elements demonstrated. - Models, Analogies, or Lab Demonstrations • All elements related to the as-corrected mirror error contributions (e.g. coatings, thermal, g-release) must be validated.
TRL 4 A low fidelity system/component breadboard is built and operated to demonstrate basic functionality and critical test environments, and associated performance predictions are defined relative to the final operating environment. ***Breadboard:*** *A low fidelity unit that demonstrates function only, without respect to form or fit in the case of hardware, or platform in the case of software. It often uses commercial and/or ad hoc components and is not intended to provide definitive information regarding operational performance.*	**Must demonstrate a credible technology development path to the required on-orbit performance of the Lynx Mirror Assembly. Demonstrations must be traceable to the on-orbit performance requirement in the operational environment.** A credible demonstration must comprise the following for these Wolter-Schwarzschild optics: - Realistic end-to-end error budget for Lynx Telescope angular resolution. - Laboratory demonstration of measured angular resolution of mirror elements performing less than a factor of **3** away from their required performance (as stated in the error budget), executed under the following conditions: • An X-ray test of a single coated, co-aligned p-s mirror pair or a mounted single, coated full shell using a breadboard lab mount must be demonstrated. Mirrors must have nominal thickness consistent with their point design. • Functional breadboard mounting and all essential hardware elements (such as fixture to hold and transport full shell elements) demonstrated. • Full shell demonstration of the alignment of a single primary shell, aligned to optical axis as defined by the mount. - Models, Analogies, or Lab Demonstrations • All elements related to the as-corrected mirror error contributions (e.g. coatings, thermal, g-release, etc.) must be validated.

TRL

NASA TRL Definition	*Milestones* for achieving TRLs for the Lynx Mirror Assembly
TRL 5 A medium fidelity system/component brassboard is built and operated to demonstrate overall performance in a simulated operational environment with realistic support elements that demonstrates overall performance in critical areas. Performance predictions are made for subsequent development phases. ***Brassboard:*** *A medium fidelity functional unit that typically tries to make use of as much operational hardware/software as possible and begins to address scaling issues associated with the operational system. It does not have the engineering pedigree in all aspects, but is structured to be able to operate in simulated operational environments in order to assess performance of critical functions.*	**Must demonstrate a credible technology development path to the required on-orbit performance of the Lynx Mirror Assembly. Demonstrations must be traceable to the on-orbit performance requirement in the operational environment.** A credible demonstration must comprise the following for these Wolter-Schwarzschild optics: - Realistic end-to-end error budget for Lynx Telescope angular resolution. - Laboratory demonstration of measured angular resolution of medium fidelity mirror brassboard sub-assemblies as defined below, performing less than a factor of 1.5 away from their required performance (as stated in the error budget), executed under the following conditions: • **Si Meta-Shell Segmented Mirrors**: X-ray test of a middle (~1.4-m diameter) structural shells with multiple full rings of segments in the middle and innermost radii of that structural shell (mass simulators used for missing optics). Demonstrate X-ray and optical performance of the three largest radii segment pairs in a single stack (not a full ring, not a meta-shell). Mirrors have nominal thickness and size consistent with their point design. • **Adjustable Segmented Mirrors**: X-ray test of partially populated module (mass simulators used for missing optics) at multiple diameters with multiple modules in the same ring (~1.4-m diameter) with modules co-aligned to one another. Demonstrate X-ray and optical performance of the three largest radii segment pairs in a single module. Mirrors have nominal thickness and size consistent with their point design. • **Full-Shell Mirrors**: X-ray test of co-aligned, coated, realistically mounted mirror pairs (p-s) of 2 diameters. Must also fabricate outermost full shell and demonstrate support structure capability and performance with metrology, or demonstrate with X-ray test largest diameter (~1.4-m) that XRCF can accommodate. Mirrors have nominal thickness and size consistent with their point design. • **Test Conditions**: Assemblies must be tested in operational environment that includes vibration and thermal vacuum. For missing mirror shells, mass simulators of sufficient fidelity must be used in the sub-assemblies. - Models, Analogies, or Lab Demonstrations • All elements related to the as-corrected mirror error contributions (e.g. coatings, g-release) must be validated.

TRL

NASA TRL Definition	*Milestones* for achieving TRLs for the Lynx Mirror Assembly
TRL 6 A high fidelity system/component prototype that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate operations under critical environmental conditions. ***Prototype:*** *The proto-type unit demonstrates form, fit, and function at a scale deemed to be representative of the final product operating in its operational environment. A subscale test article provides fidelity sufficient to permit validation of analytical models capable of predicting the behavior of full-scale systems in an operational environment.*	**Must demonstrate using a high-fidelity scalable flight-like prototype which adequately addresses all critical scaling issues that all Lynx performance requirements are met in critical environments.** A credible demonstration must comprise the following for these Wolter-Schwarzschild optics: -Environmental testing (acoustic, thermal vacuum, vibration, radiation) and X-ray testing in operational environments. - Models, Analogies, or Lab Demonstrations • All elements related to the as-corrected mirror error contributions (e.g. g-release) must be validated.

LMAT Working Group Participants

Stakeholders (on behalf of the STDT)

Feryal Ozel	University of Arizona
Alexey Vikhlinin	Harvard SAO
Jessica Gaskin	NASA MSFC

Steering Group

Feryal Ozel	University of Arizona	
Alexey Vikhlinin	Harvard SAO	
Jessica Gaskin	NASA MSFC	
Robert Petre	NASA GSFC	
Doug Swartz	NASA MSFC	
Jon Arenberg (Bill Purcell/Lynn Allen)	NGAS (Ball/Harris)	
Jaya Bajpayee	NASA ARC	consensus member
Gabe Karpati	NASA GSFC	consensus member
Mark Schattenburg	MIT	consensus member

Facilitator

Gary Blackwood	NASA ExEP/ JPL

Subject Matter Experts, Observers and Guests (Members will be added as ne

Denise Podolski	NASA STMD
Rita Sambruna/Dan Evans	NASA HQ
Terri Brandt/Bernard Kelly	NASA PCOS
Vadim Burwitz	MPE
Susan Trolier-McKinstry	Penn State
Casey DeRoo	U. Iowa
TBD	Optics Working Group
TBD	Optics Working Group
TBD	Optics Working Group
Dan Schwartz	**Harvard SAO**
Steve Bongiorno	**MSFC**
Kurt Ponsor	**Mindrum Precision (OWG)**
~~Bernd Aschenbach~~	~~AXRO~~

Consensus Members

Members at Large

1.	Mark Schattenburg	MIT	

Advocates

2.	Kiran Kilaru	USRA / MSFC	Full Shell
3.	Giovanni Pareschi	INAF / OAB	Full Shell
4.	William Zhang	NASA GSFC	Metashell Silicon
5.	Peter Solly	NASA GSFC	Metashell Silicon
6.	Paul Reid	Harvard SAO	Adjustable Segmented
7.	Eric Schwartz	Harvard SAO	Adjustable Segmented

Science Evaluation Team (SET)

8.	Daniel Stern	NASA JPL	
9.	Frits Paerels	Columbia University	SET Lead
10.	Ryan Hickox	Dartmouth	

Technical Evaluation Team (TET)

11.	Gabe Karpati	NASA GSFC	TET Lead
12.	Ryan McClelland	NASA GSFC	structural/thermal
13.	Lester Cohen	Harvard SAO	structural
14.	Gary Mathews	retired Kodak	systems engineering
15.	Mark Freeman	Harvard SAO	thermal / SE
16.	David Broadway	NASA MSFC	coatings
17.	Dave Windt	private company	coatings
18.	Marta Civitani	OAB	optical design, test
19.	Paul Glenn	private company	metrology
20.	Ted Mooney	Harris	polishing
21.	Chip Barnes	Ball	systems engineering

Programmatic Evaluation Team (PET)

22.	Jaya Bajpayee	NASA ARC	PET Lead
23.	John Nousek	Penn State	
24.	Karen Gelmis	NASA MSFC	
25.	Steve Jordan	Ball	
26.	Charlie Atkinson	NGAS	

Links to Key Supporting Documents

- The LMAT Charter can be found: HERE
- All LMAT materials (requests to mirror technology teams and their responses) can be found: HERE
  - Requests to mirror technology teams: HERE
  - Responses from mirror technology teams: HERE

Silicon Meta-shell Optics (SMO) Technology Development Roadmap

William W. Zhang & Peter M. Solly
for
The Next Generation X-ray Optics Team
at
NASA Goddard Space Flight Center

Next Generation X-ray Optics (NGXO) Team

K.D. Allgood[1], M.P. Biskach[1], J. Bonafede[1], K.W. Chan[2], M. Hlinka[1], J.D. Kearney[1], L.D. Kolos, J.R. Mazzarella[1], G. Matthews[3], R.S. McClelland, H. Mori[2], A. Numata[1], T. Okajima, L.G. Olsen, R.E. Riveros[2], T.T. Saha, P.M. Solly[1], W.W. Zhang

NASA Goddard Space Flight Center
[1] also Stinger Ghaffarian Technologies, Inc.
[2] also University of Maryland, Baltimore County
[3]also ATA Aerospace, LLC

Work funded by NASA through GSFC/IRAD, ROSES/APRA, and ROSES/SAT.

Principles Guiding the NGXO Work

- Keep it simple.
  - Simplicity → High reliability, low cost, and elegance.
  - Complexity → Low reliability, high risk, and high cost.
- Keep it traditional as much as possible.
  - Don't reinvent the wheel. Don't innovate for the sake of innovation.
  - Innovate only when necessary to solve real problems.
- Test, test, and test (or measure, measure, and measure).
  - Don't accept any claim from anybody, especially from yourself unless/until it is backed up by empirical evidence.
  - Don't trust any model or analysis or simulation or prediction unless/until it has been empirically verified.
  - Don't trust any empirical result unless/until it has been repeated at least three times and understood with analysis and modeling.

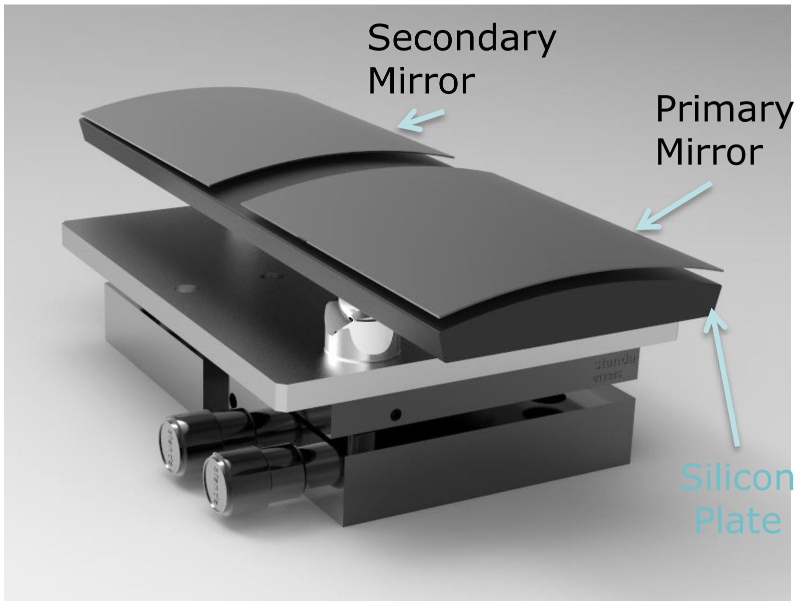
Key Features of the Silicon Meta-Shell Approach

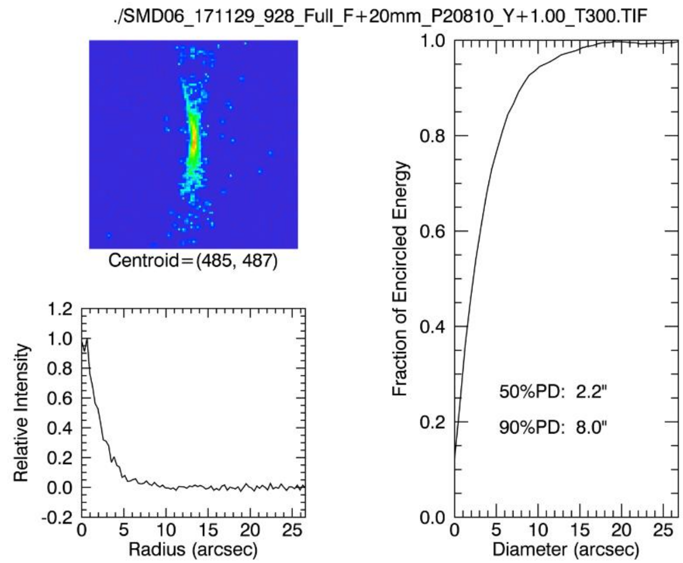
- Potential for great (or diffraction-limited) PSF, low mass, and low cost
  - Perfection of the process can lead to diffraction-limited X-ray optics.
  - Refinement and automation can lead to very low cost.
- Traditional and innovative: build, test, and fly
  - Optimal combination of tradition and innovation, and
  - Incorporation of lessons and knowledge of all past X-ray missions.
- Use of commercially off-the-shelf materials, components, and equipment
  - Short lead time, low cost, and reliable sources.
  - Many parallel production lines can be set up quickly and inexpensively.
- Scalable to building mirror assemblies for missions of every size, from SMEX, to MIDEX, Probes, and Flagships like Lynx
  - Production lines: mirror fabrication, coating, alignment and bonding, each can be built using only COTS equipment and materials.
  - Many production lines can be set up in one or more geographic locations to meet schedule and risk reduction requirements.

Heritage of Silicon Meta-Shell Optics

- BBXRT, ASCA, Suzaku, & Hitomi
  - Segments and their mass production to minimize cost and schedule.
  - Use small, off-the-shelf equipment to build big mirrors.
- *Einstein*, ROSAT, & *Chandra*
  - Precision polishing, the only way so far to make the best possible optics.
- XMM-Newton
  - Fastening a mirror shell at only one end to a spider, minimizing over-constraint and therefore distortion.
- NuSTAR
  - Aligning and bonding mirrors one by one. It can be done and can be done on schedule and on budget.

SMO Basic Process Validated by X-ray Testing





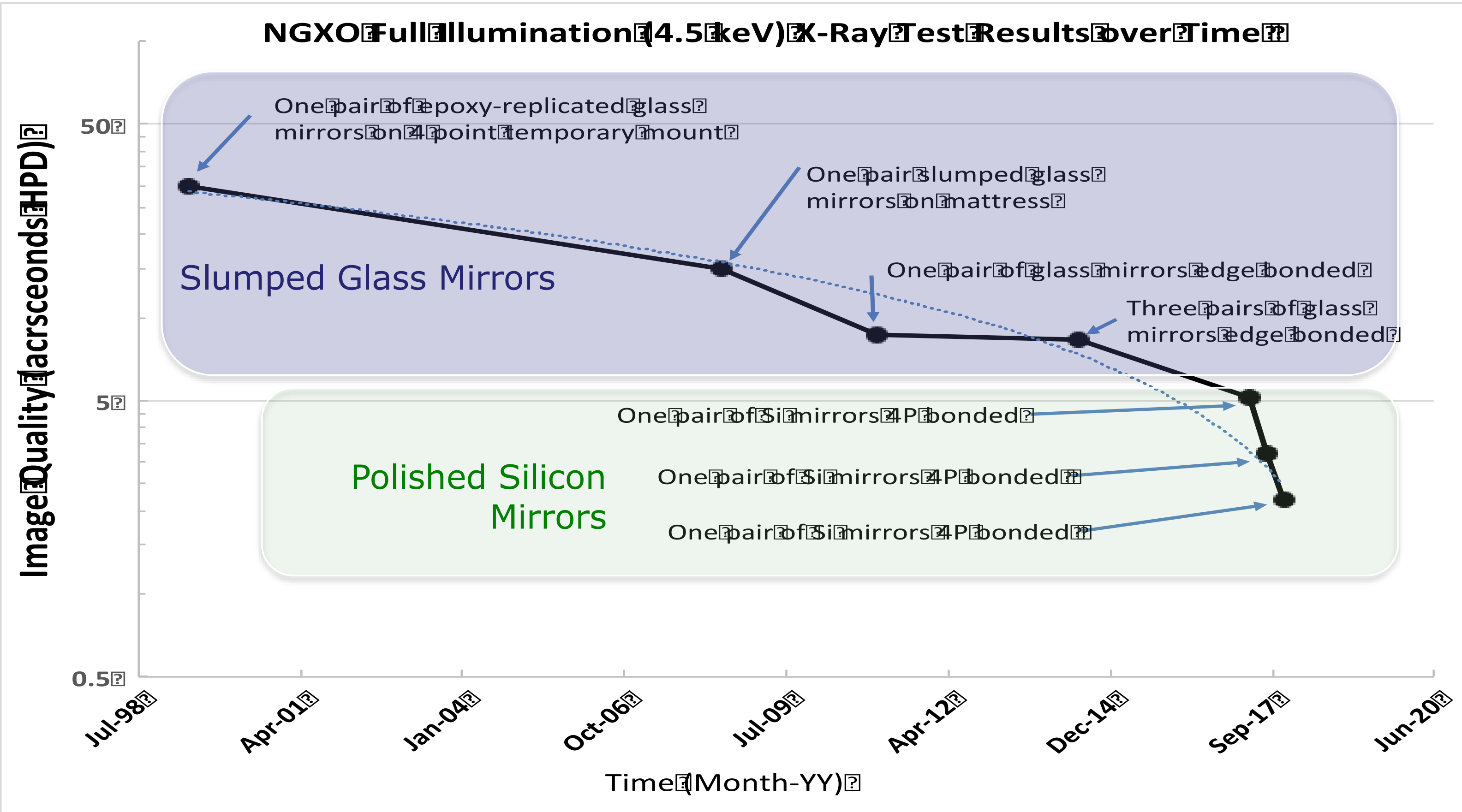
Two uncoated mono-crystalline silicon mirrors aligned and bonded on a silicon platform

Full illumination with Ti-K X-rays (4.5 keV)

Effective Area at Ti-K (cm²): 0.266 predicted, 0.260 measured, 2.3% deficit.

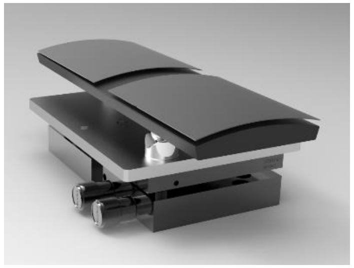
Acknowledgement: Thanks to Vadim Burwitz and his team at Panther who performed this measurement.

Steady & Accelerating Progress over the Years



SMO Key Challenges/Tasks for Meeting TRL

Single-Pair Modules (TRL-4)



Objectives:

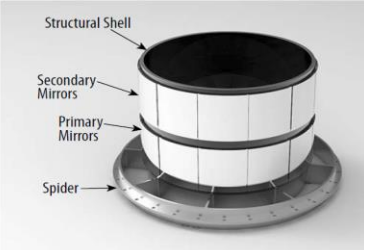
1. Develop and verify mirror fabrication and mirror coating processes.
2. Develop and verify the basic elements of alignment & bonding procedures for precision and accuracy.

Multiple-Pair Modules (TRL-5)

Objectives:

1. Develop and verify mechanics and speed of co-alignment and bonding processes.
2. Conduct environmental tests: vibration, thermal vacuum, and acoustic to verify structural and performance robustness.

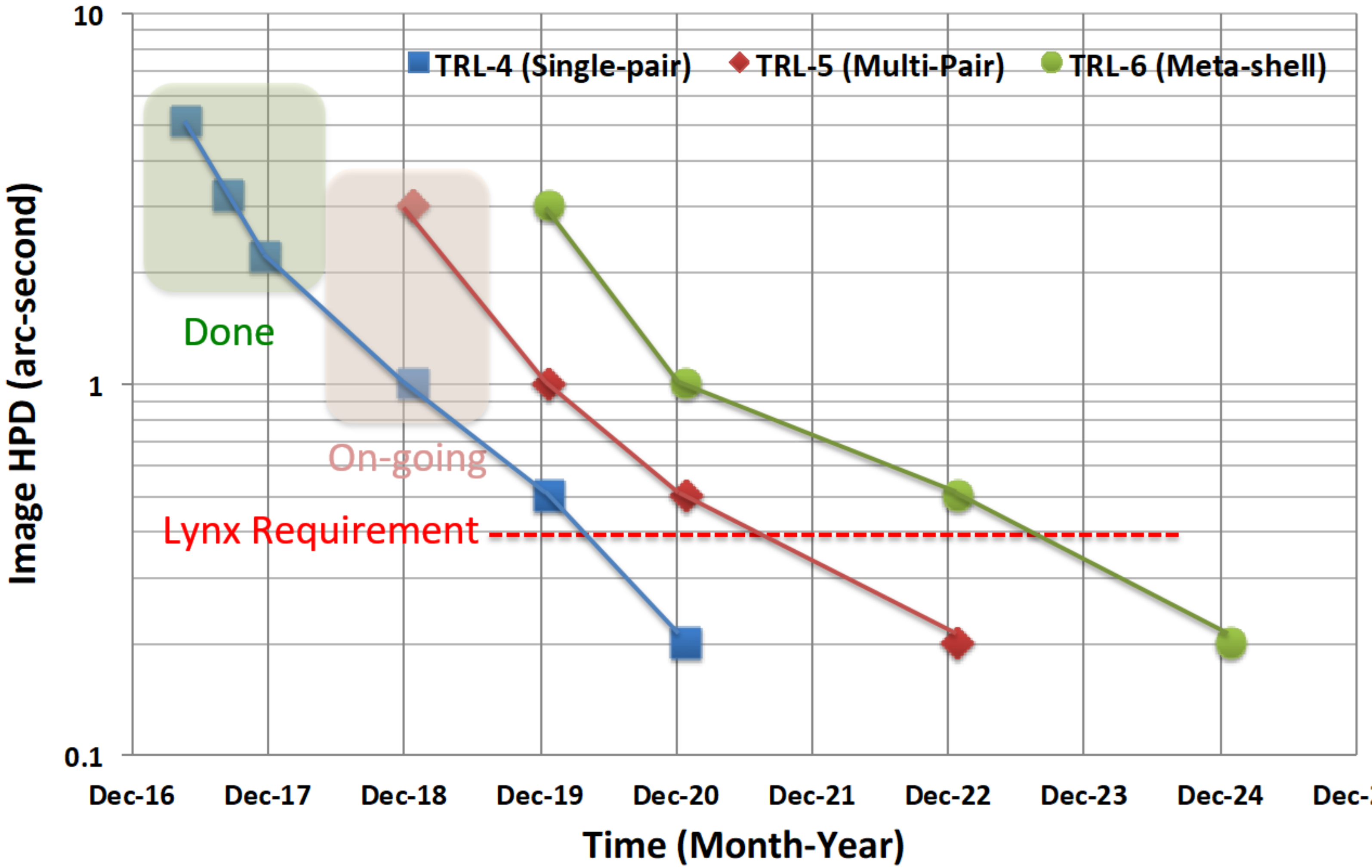
Meta-Shells (TRL-6)



Objectives:

1. Develop and verify all aspects of meta-shell production process: mirror fabrication, coating, alignment, and bonding.
2. Validate production schedule and cost estimates.
3. Develop and plan for mass production.

In Pursuit of TRLs: Reality and Expectations



Mirror Assembly Error Budget & Status & Mitigation

Source of Error		Allocation or Requirement (arcsec HPD)	State of the Art (arcsec HPD)	Determination & Verification	How to Bridge the Gap between State-Of-Art and Requirements
Optical Prescription	Diffraction	0.10	0.10	At 1 keV, from calculation based on optical prescription. This is the weighted (by effective area) mean of all the mirror shells/segments. The innermost shell has diffraction-limited HPD of 0.41" whereas the outermost 0.038".	N.A.
	Geometric PSF (on-axis)	0.00	0.00	Wolter-Schwarzschild prescription. It has geometrically perfect image on-axis, and 1" and 0.4" HPD at 10' off-axis for a flat focal plane and an optimally curved focal surface, respectively.	N.A.
Mirror Segment Fabrication	Mirror Substrate	0.20	0.50	This number includes all possible errors for a pair of substrates. Based on normal incidence optical measurement done for each mirror substrate, and on x-ray measurement done for select mirror substrates.	The 0.5" has been achieved with only a single pass on an ion-beam figuring machine. We expect that a second pass will bring the mirror to not only meet the 0.2" requirement, but probably much better than 0.2". This will be done once we have our own IBF machine in December 2018.
	Coating	0.10	0.20	For a pair of primary and secondary mirrors. Based on normal incidence measurements of substrates before and after coating, and on x-ray measurement of select mirror segments.	The current 0.2" has been achieved with balancing Ir-coating stress on the front and back of the mirror. Going forward we will use thermally-grown SiO2 on the backside to balance the Ir-coating stress on the front. The fine tunning of balance will be done by trimming the thickness of the SiO2 layer using either chemical means (HF etchcontrolled by a mask, done at MIT) or "mechanical" means (ion-beam figuring).
Meta-Shell Construction	Alignment	0.10	1.60	This number includes the precision of spacer heights, error of settling the mirrors. It is for a pair of primary and secondary mirrors. Based on Hartmann measurements conducted with both visible light and x-rays.	We need to improve spacer heights precision and improve the alignment beam quality: wavefront and temporal staility. Furthermore we need to improve the laboratory environment stability, including both thermal and vibrational stability.
	Bonding	0.20	0.40	This number includes the application of epoxy, its cure, and other effects related to bonding. It is for a pair of primary and secondary mirrors. Based on finite elment analysis and modeling of epoxy cure effect and on Hartmann measurements using x-rays.	The 0.4" has achieved with four round posts, each of which is about 3 mm in diameter and with a conical dome. Going forward we will change this geometry to a rectangular one of 1 mm by 3 mm which will have a lot less potential for causing local or global distortion of the mirror.
Integration of Meta-shells to XMA	Alignment	0.10	0.10	This number respresents the ability to orient and translate and verify the alignment of a meta-shell. Based on optical Hartmann measurements and fiduciary laser beams.	N.A.
	Attachment	0.10	0.22	Based on optical alignment verification and end-to-end x-ray measurements.	The 0.22" is based on an initial place-holder design of an attachent mechanism. This design will be iterated and optimized to reduce its distortion.
Ground to Orbit Effects	Launch Shift	0.10	0.10	Based on finite element analysis and modeling supported by empirical data of epoxy creep and long term stability.	N.A.
	Gravity Release	0.10	0.14	Based on finite element analysis and modeling which is verified by both optical and x-ray measurement of large numbers of trials of individual mirror pairs in different orientations with respect to gravity.	The 0.14" contains inacuracies of our ray-trace code. We believe that the real effect is actually meeting the 0.10" requuirement already. This will be looked at once personnel and recources become available for Lynx.
	On-orbit thermal	0.10	0.16	Based on thermal modeling and analysis.	The 0.16" contains inacuracies of our ray-trace code. We believe that the real effect is actually meeting the 0.10" requuirement already. This will be looked at once personnel and recources become available for Lynx.
On-Orbit Performance (RSS)		**0.40**	**1.77**	This is the on-axis performance of the mirror assembly on orbit. Add effects of jitter and detector pixellation to get the final obervatory-level PSF.	N.A.

See Error Budget in the ExcelBook for an easier-to-read version.

Demonstration of TRL-4 for Lynx

- Requirement: Build and X-ray test single-pair modules to achieve better than 1.0” HPD images at 1 keV.
  - Focal length: 8,400mm.
  - Diameter of the mirrors: ~310mm.
  - X-ray tests to be done at both GSFC and MPE/Panter (thanks to Dr. Vadim Burwitz.)
- Current Status
  - Built and tested un-coated mirrors and achieved 2.2” HPD images (See Slide#7).
- What To Do
  - Perform 2nd pass ion-beam figuring on mirrors;
  - Coat mirrors with Cr+Ir on the concave side and SiO_2 on convex side;
  - HF-trimming or IBF-trimming the SiO_2 layer to precisely balance stress of iridium coating.
- Schedule
  - March 2019: at least 3 iterations (single-pair modules) of the above process will be done.
- Technical Risk
  - Metrology: the measurement system may not provide sufficiently accurate map for the ion-beam figuring machine to finish the mirror correctly.
  - Epoxy bonding: the epoxy bonding may cause larger than expected distortion and misalignment.

Demonstration of TRL-5 for Lynx

- Work will be done in two phases
  - Phase-1 addresses technical problems, and
  - Phase-2 addressed logistical problems.
- Phase-1: Technical preparation by repeatedly building and testing multi-pair modules with following characteristics
  - Focal length: 8,400mm,
  - Mirror diameters: ~310mm, and
  - Number of pairs per module: 3
- Phase-2: Building and testing a meta-shell per Lynx definition
  - Focal length: 10,000mm,
  - Meta-shell diameter: 1,400mm,
  - Number of pairs in meta-shell: 1,560, most of which can be mass dummies.

Technical Preparation for TRL-5 Demo

- Build 3-pair modules with existing tooling
  - Focal length: 8,400mm,
  - Diameters: ~310mm,
  - Mirror segments quality: better than 0.5" HPD,
  - Mirror segment thickness: 0.5mm,
  - Mirror coating: 30nm iridium with 5nm chrome under-layer for binding and SiO2 on the backside for stress cancellation.
- X-ray and environmental testing
  - X-ray images: 0.5" HPD at 1 keV
  - X-ray tests to be done at GSFC and MPE/Panter,
  - Vibration and thermal vacuum tests at GSFC or MPE/Panter,
  - Shock tests to be done at GSFC.
- Schedule
  - March 2020: at least two modules per above specification will be built and tested.
- Technical Risk
  - No risk here, provided the metrology risk and epoxy bonding risk have been retired in demonstrating TRL-4.

Building a Meta-Shell Demo TRL-5 for Lynx

- Meta-shell per Lynx definition
  - Focal length: 10,000mm,
  - Meta-shell diameter: 1,400mm,
  - Number of mirror segments: 3,120, some of which can be dummies.
- X-ray and environmental tests
  - The same as on previous page, and
  - X-ray image quality: ~0.5" HPD at 1 keV.
- Work to be done
  - Procure necessary equipment and materials, establishing a mirror fabrication factory and meta-shell production line.
  - Repeat the fab-coating-alignment-bonding process 3,120 times to build this meta-shell.
  - Conduct performance tests and environmental tests.
  - This represents a major production and test effort, far beyond what our technology development program can accommodate.
- Schedule
  - Work could begin in April 2020, finish in September 2023, provided adequate funding would be made available.
- Technical risk
  - None.
- Logistical Risk
  - Epoxy cure time may be a bottle-neck in preventing the TRL-5 from completing according to schedule.
- Programmatic risk
  - Inadequate funding. It is unlikely that we can get the funding to do this demonstration outside the Lynx project.
  - This work may be predicated on Lynx being fully endorsed by the Decadal Survey because this work represents a major undertaking that can only take place for a real project.

Demonstration of TRL-6 for Lynx

- Build and fully test, both performance and environmental, a meta-shell with the following characteristics
  - The same as for TRL-5 except that all mirror segments must be fully qualified mirrors.
  - X-ray performance, both before and after environmental tests, must be better than 0.4" HPD. It also must meet all other requirements that may be part of the science requirements, such as FOV, effective areas at different energies, PSF tails, etc.
- Work to be done
  - The work and equipment here are substantially similar to those for TRL-5, the difference being that they are more rigorous and more in magnitude. No additional equipment is expected.
- Schedule
  - Work could begin in October 2023, complete by September 2027, provided adequate funding would be made available.
- Technical Risk
  - None once TRL-5 has been successfully demonstrated.
- Programmatic Risk
  - This work will only happen if and when Lynx enters Phase-A, providing sufficient funding and clout.

Technical Challenge: Metrology

- Description of the challenge
  - Both the mirror fabrication and coating processes depend on accurate measurement of the mirror segment to correct the figure error.
  - The measurement may contain unacceptably high systematic error caused by reference flat in the Fizeau interferometer and a null lens.
- How to meet the challenge
  - Work with the National Institute of Standards and Technology (NIST) to calibrate the reference flat and the null lens wave front.
  - Compare images based on optical measurement data with high-fidelity X-ray images, including Hartmann images, to arrive at corrections to the optical measurements.
- Risk
  - The amount of work required may have to wait until Lynx is endorsed by the Decadal and has entered pre-Phase-A to have adequate resources to support a rigorous effort to solve the metrology problem.

Technical Challenge: Epoxy Cure Stress & Time

- Description of the challenge
  - Epoxy cure could stress the mirror, causing both local and global distortion, leading to figure and alignment errors.
  - Epoxy takes time to cure and could be a bottle neck in building meta-shells.
- How to meet the challenge
  - We are investigating using precision silicon combs fabricated by a combination of the photolithographic process and the deep-reactive ion etching process. Such combs will replace the individually-made spacers, and will allow many mirrors to be aligned one by one and then bonded altogether at once.
  - If these combs work well, they will completely address both the distortion problem and the cure time problem
    - The distortion problem is at least mitigated, possibly eliminated completely, by the fact that each bond on each mirror is several times smaller, therefore many times smaller in potential stress.
    - The cure bottleneck problem is eliminated by curing the bonds of many mirrors at once.
- Risk
  - Risk of this new process will be assessed once several trials have been done. At the present time, we are not aware of any risk.