Precision-Polished Mono-Crystalline Silicon Mirrors for Athena

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Next Generation X-ray Optics (NGXO) Team

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Outline of Presentation

- **Introduction to NGXO**
  - Brief history of our technology development.
  - Our objectives and overall approach achieve them.
- **Technology**
  - Mirror Fabrication.
  - Mirror Coating.
  - Mirror Alignment.
  - Mirror Bonding.
- **Engineering**
  - Optical design, analysis, and stray light baffling.
  - Structural design, analysis, and testing.
  - Thermal design and analysis.
  - Effect of gravity release.
- **Production**
  - Equipment.
  - Personnel.
  - Schedule.

A Brief History of the NGXO Team

- **2001: Established to develop X-ray optics for Con-X/IXO.**
  - 2001-2011: Funded by NASA's Con-X and IXO project offices.
  - 2012-present: funded by NASA through GSFC/IRAD, ROSES/APRA and ROSES/SAT.
- **2009-2012: Built three mirror assemblies for NuSTAR.**
  - Teamed with Columbia Univ., DTU, and LLNL.
  - Made 12,000, coated, and assembled 8,000 slumped glass mirror segments.
- **2011-2014: Advanced glass slumping technology to enable ~10" X-ray telescopes.**
  - Built and tested modules with 3 pairs of mirrors: ~7" HEW.
  - Gave up glass slumping for several reasons. See next slide.
- **2015-Present: Developing polished silicon X-ray optics to meet three-fold requirement of future missions, including Lynx, AXIS, TAP, HEX-P, FORCE, STAR-X, & OGRE.**
  - High angular resolution,
  - Large effective area (or lightweight), and
  - Low production cost.

Why We Gave Up On Slumped Glass

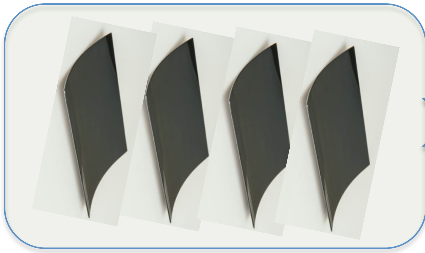
- **Components Level: Slumped glass's figure is not good enough for better than 5" PSF.**
  - Best achieved: ~6" HPD (Wolter-I, two reflections).
  - Little or nearly no progress between 2010 and 2013.
- **Systems Level: Slumped glass's thermal properties make it hard, if not practically impossible, to realize better than ~5" PSF.**
  - High thermal expansion.
  - Low thermal conductivity.
  - Resulting in large thermal degradation to PSF: **6.6"** HPD under reasonable assumptions.
- **Mission Implementation: Glass slumping requires mandrels that are difficult, if not practically impossible, to make.**
  - Mandrels, being convex, are difficult to measure and therefore difficult to make.
  - Although technically feasible, mandrels are expensive and time-consuming to make.
  - Mandrels create an almost insurmountable logistical problem for making large mirror assemblies.
- **Something much superior: polished mono-crystalline silicon mirrors.**

NGXO'S Objectives

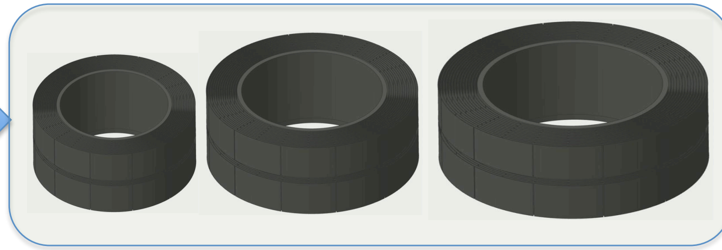
- **Near Term (2 to 5 years)**
  Develop for X-ray astronomy a mirror technology that has the following characteristics compared to those of Chandra's.
  - Point-Spread-Function: better than 0.5" HPD (HEW).
  - Effective Area: at least 10X to 50X larger per unit mass.
  - Production Cost: at least 10X to 30X less expensive per unit effective area.
- **Long Term (5 to 10 years)**
  Achieve diffraction-limited PSF while maintaining the effective area and production cost advantages.
  - ~0.1" HPD (HEW) at 1 keV for current parameters of mirror design.

Fundamentals of Silicon Meta-shell Optics

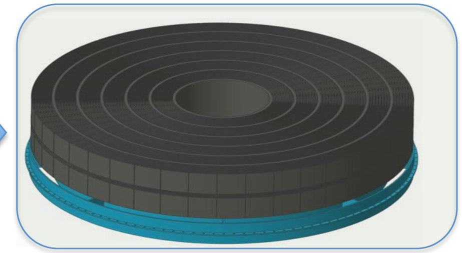
Three-Level Hierarchy



1. $\sim 10^4$ Mirrors



2. $\sim 10^1$ Meta-shells



3. 10^0 Assembly

Four Technical Elements

1. Precision-polishing of Mono-crystalline silicon.

2. Coating to maximize reflectivity w/o distortion.

3. Alignment with kinematic support: 4 points per mirror.

4. Permanent bonding w/o frozen-in distortion.

Two Foundational Principles

1. Mono-crystalline silicon can be processed deterministically because it has no internal stress.

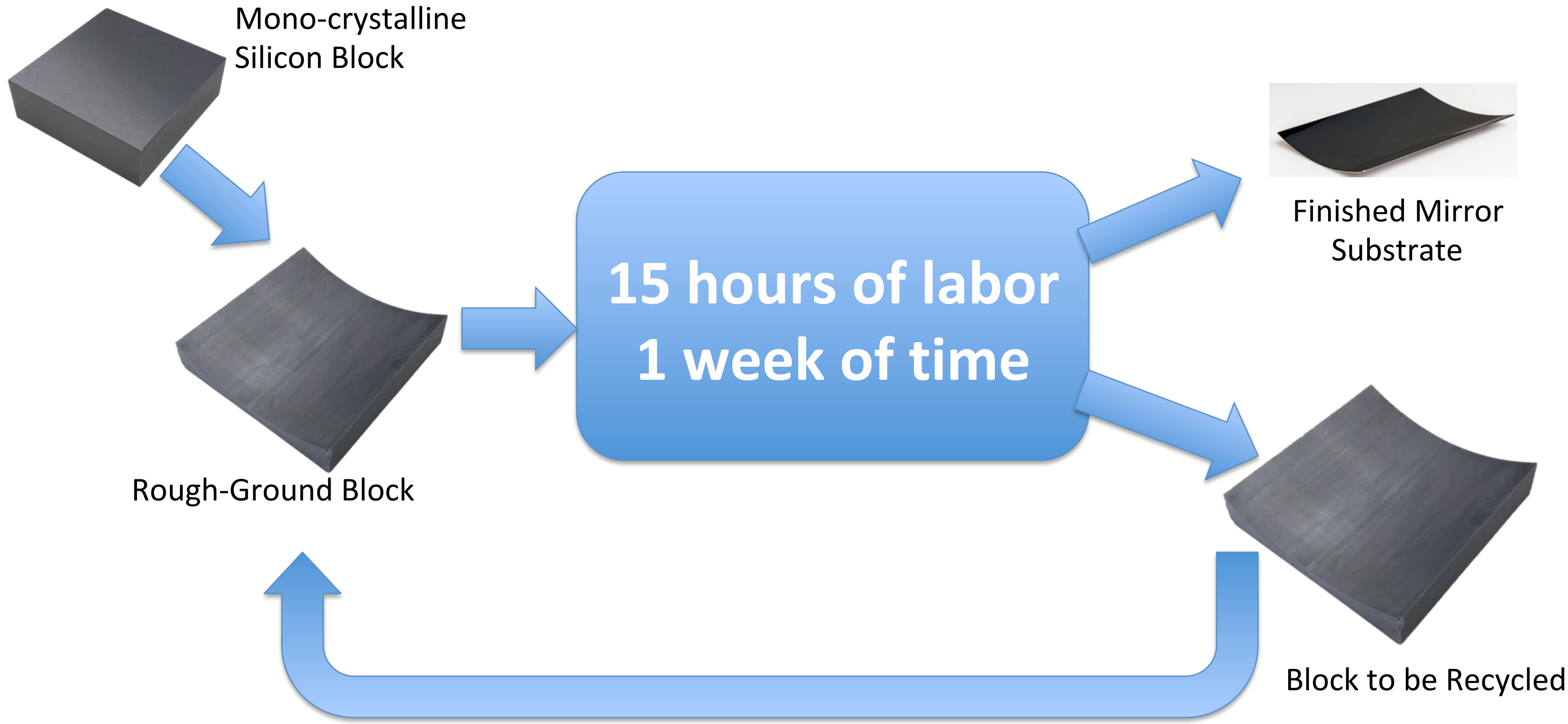
2. An X-ray (curved) mirror's location and orientation are kinematically determined by four points.

Technology

Technology Development

- **Four basic technical elements underlying our technology**
  - Mirror fabrication: from blocks of silicon to thin mirrors.
  - Mirror coating: maximizing reflectance with minimal distortion.
  - Mirror alignment: making mirror supports with sub-µm precision.
  - Mirror bonding: strong & fast bonding with minimal distortion.
- **These four technical elements are critically important**
  - The building of a mirror assembly is just a repetition of these four steps for ~10^4 times.
  - The performance, reliability, and cost of these technical elements directly impact the performance, schedule, and cost of the mission.

Mirror Fabrication Process



Mirror Fabrication Steps

- Grinding to impart rough conical shape,
- Lapping to impart radius and cone angle,
- Slicing to make a lightweight substrate,
- Chemical-etching to remove damage to crystal,
- Stress-polishing to reach ~3” HEW figure,
- Smoothing to achieve ~2 Å micro-roughness,
- Grinding to achieve precise thickness,
- Trimming to remove poor quality areas near edges,
- Chemical-etching to remove damage caused by grinding,
- Ion-beam-figuring to achieve final figure: ~0.5” HEW.

Sub-arc-second, 0.5mm thick, mirrors are fabricated on a routine basis.

Mirror Coating Process

Bare Silicon

Mirror

2 hours of labor
2 days of time

Concave Side: Cr + Ir
Convex Side: SiO_2

Coated Mirror

Work done in collaboration with MIT: Y. Yao, B. Chalifoux, and M. L. Schattenburg.

Mirror Coating Steps

- **Coat a mirror on both sides to achieve near cancellation of stress**
  - On the concave side: ~5 nm of chromium and ~30 nm of iridium.
  - On the convex side: ~300 nm of silicon oxide.
  - For the most part, the stresses on the two sides of the mirror cancel each other.
- **Trim the silicon oxide layer (using chemical etch or ion-beam figuring) to achieve complete and exact stress cancellation.**
  - Measure figure distortion after coating.
  - Use finite element analysis to calculate a stress field and to convert the stress field into a thickness map.
  - Use the thickness map as the guide to trim the thickness of the silicon oxide layer.

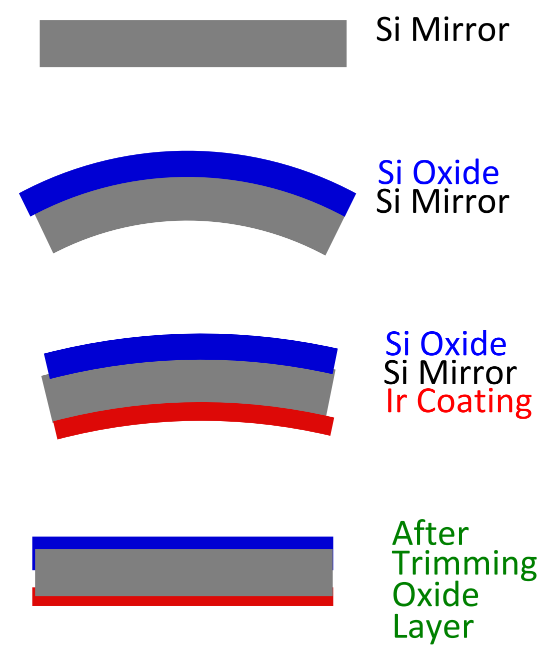
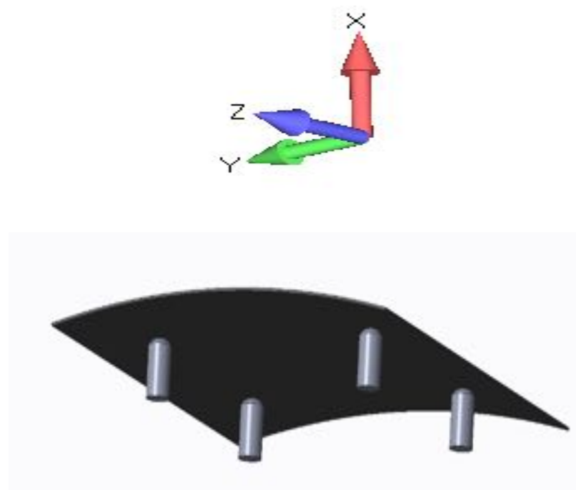


Figure distortion due to coating stress has been reduced to < 0.2” HPD.

Mirror Alignment Steps

- **Four-point kinematic support**
  - Mathematically and empirically proved to be kinematic.
  - Locations optimized to minimize gravity distortion and gravity release error.
- **Use gravity as nesting force**
  - Most reliable and repeatable force.
  - Always and freely available.
- **Use precision-lapping to achieve alignment**
  - Deterministic and efficient.
  - Highly amendable to robotic operations.
- **Use vibration to settle the mirror**
  - Overcomes static friction.
  - Relaxes the mirror to its natural shape.



X – Gravity
Y – Circumferential
Z – Optical Axis

Mirror segment's focus centroid is routinely aligned to an accuracy of 0.2", with a focus quality of 1.2" HPD.

Mirror Alignment: Two Methods Under Development

Under development for the past two years

Misaligned Mirror

Using Posts/Spacers

~10 hours of labor

~ 1 week of time

Alignment Mirror

Development initiated a month ago

Misaligned Mirror

Using silicon combs

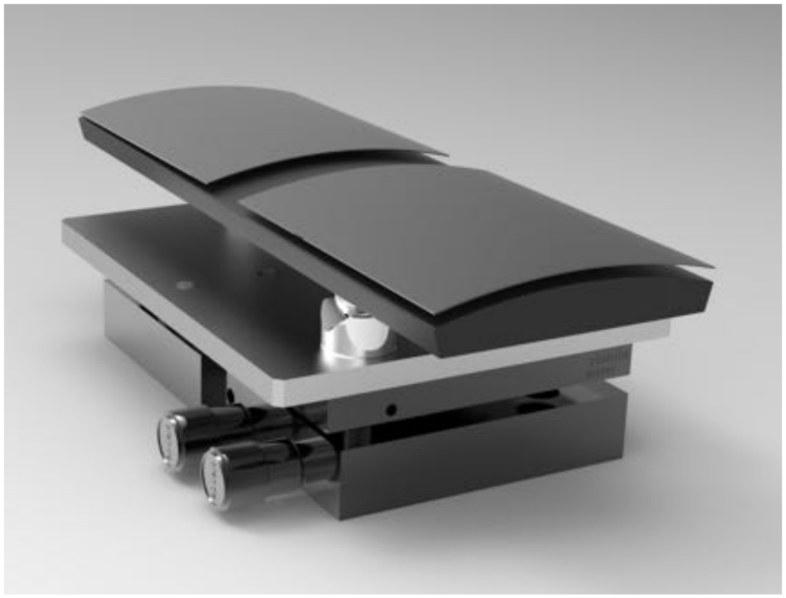
~1 hour of labor

~ 2 hours of time

Alignment Mirror

We expect to transition to silicon combs by the end of 2018.

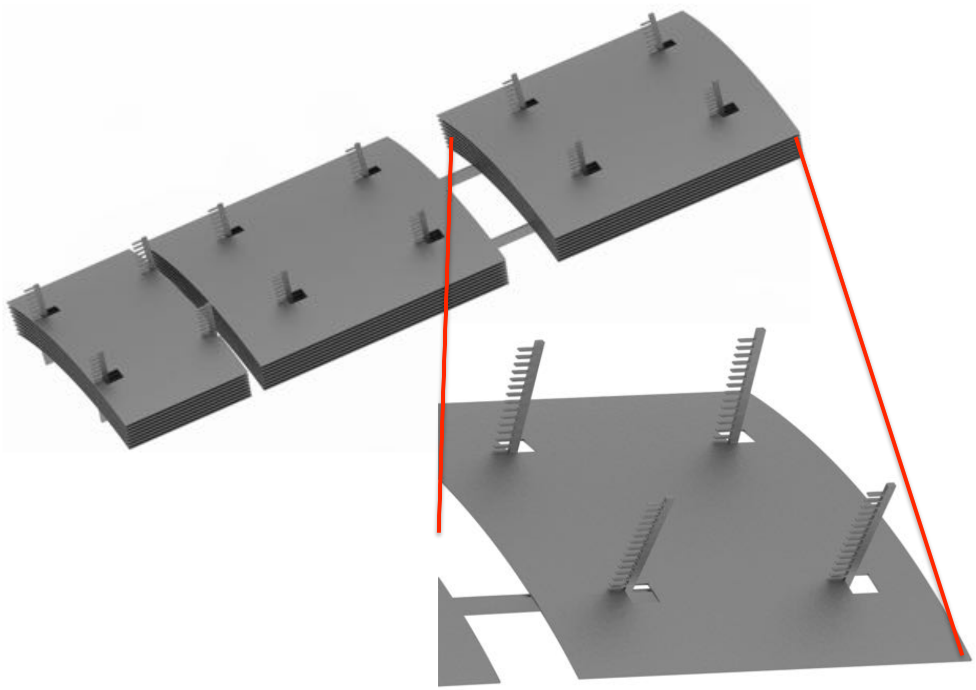
Mirror Alignment Using Posts (aka Spacers)



- **Each mirror is supported by four posts (or spacers), not visible here.**
- **The heights or these four posts determine the location and orientation of the mirror.**
- **Their heights are precisely machined to an accuracy better than 100 nm.**
- **Optical Hartmann measurements are used to determine their heights.**

This way of aligning mirrors has been done repeatedly, demonstrating the principle of aligning a mirror using four supports.

Mirror Alignment Using Silicon Combs



- **Following the same principle, but replace large numbers of spacers with precision-micro-machined combs.**
- **These combs are fabricated using photolithography and deep reactive ion etching process: precise, and inexpensive.**

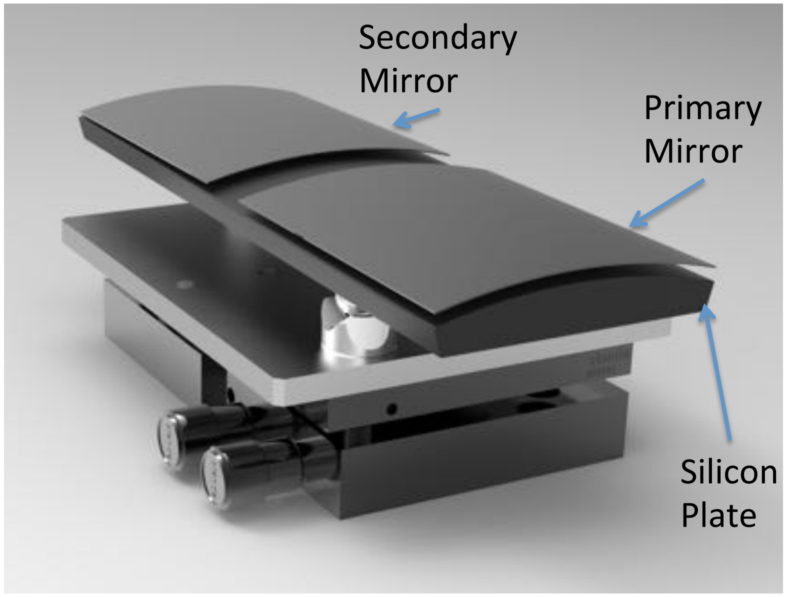
Advantages: 1. Combs are much easier and cheaper to make than spacers;
2. Many mirrors can be aligned and bonded at once; and
3. Each mirror only bears its own load.

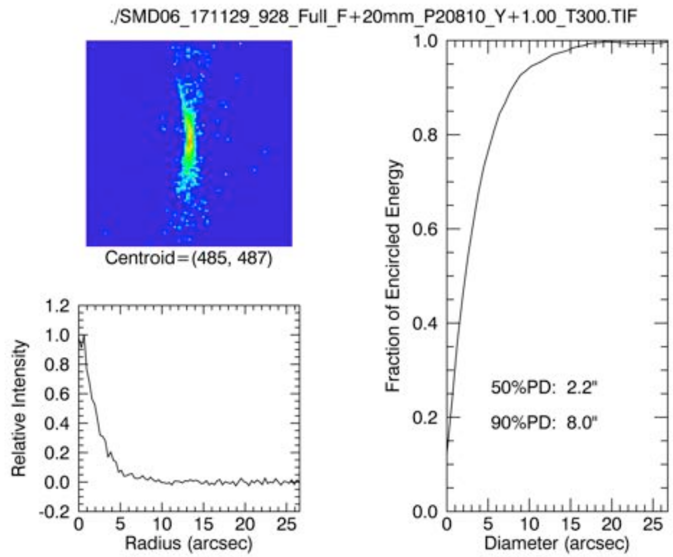
Mirror Bonding

- **Remove the mirror from the four spacers,**
- **Apply a trace-amount of adhesive on top of each spacer,**
- **Re-place the mirror back on the spacers,**
- **Use vibration to settle the mirror into alignment, and**
- **Let adhesive cure.**

Alignment shift and figure distortion due to bonding are < 0.5” HPD.

Process Validated by X-ray Testing





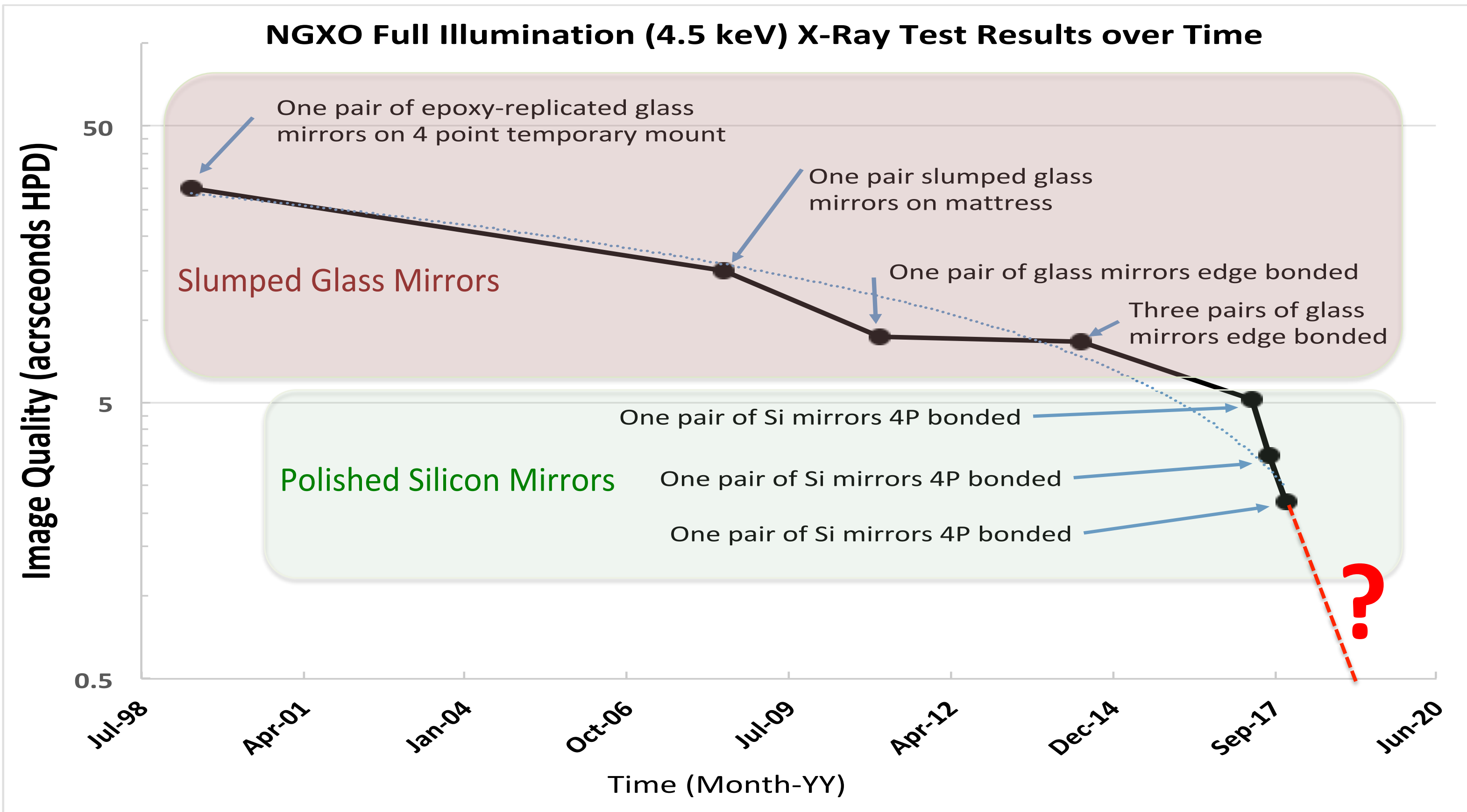
Two uncoated mono-crystalline silicon mirrors aligned and bonded on a silicon platform

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

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

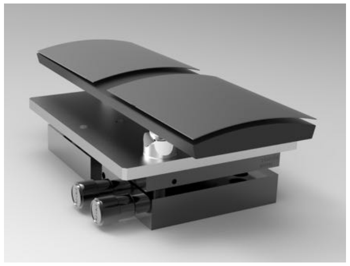
Acknowledgement: Thanks to Vadim Burwitz and his team at Panther who performed this measurement.

NGXO Progress over the Years



In Pursuit of TRLs: Three Prongs

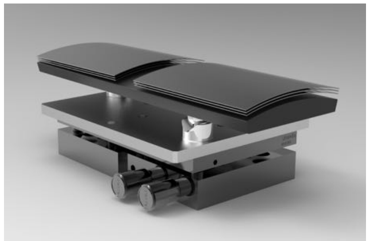
Single-Pair Modules (TRL-4)



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.

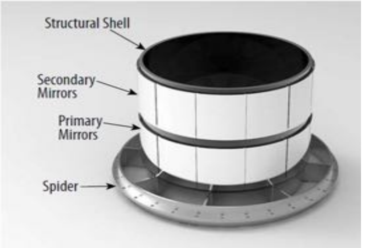
Multiple-Pair Modules (TRL-5)



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.

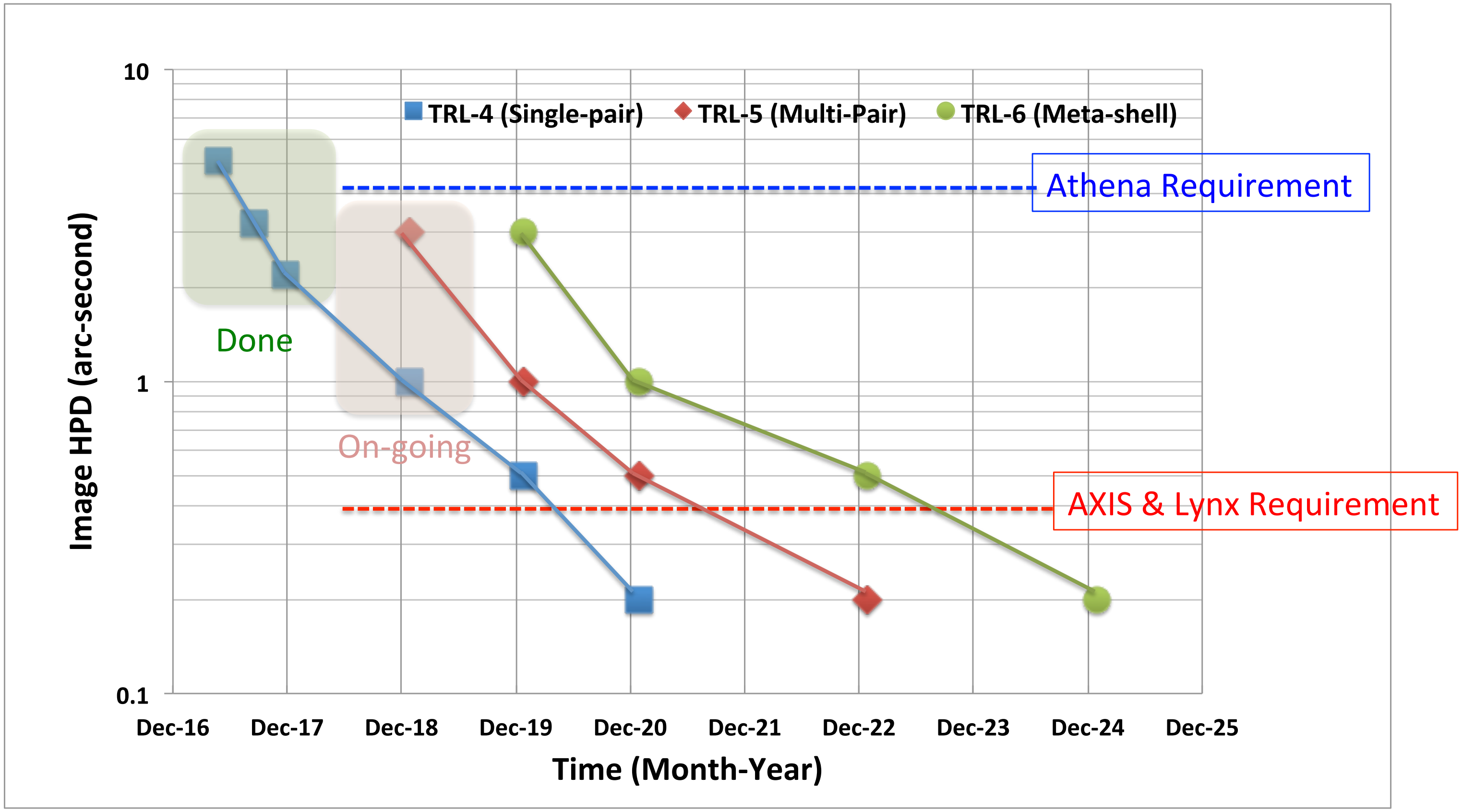
Meta-Shells (TRL-6)



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



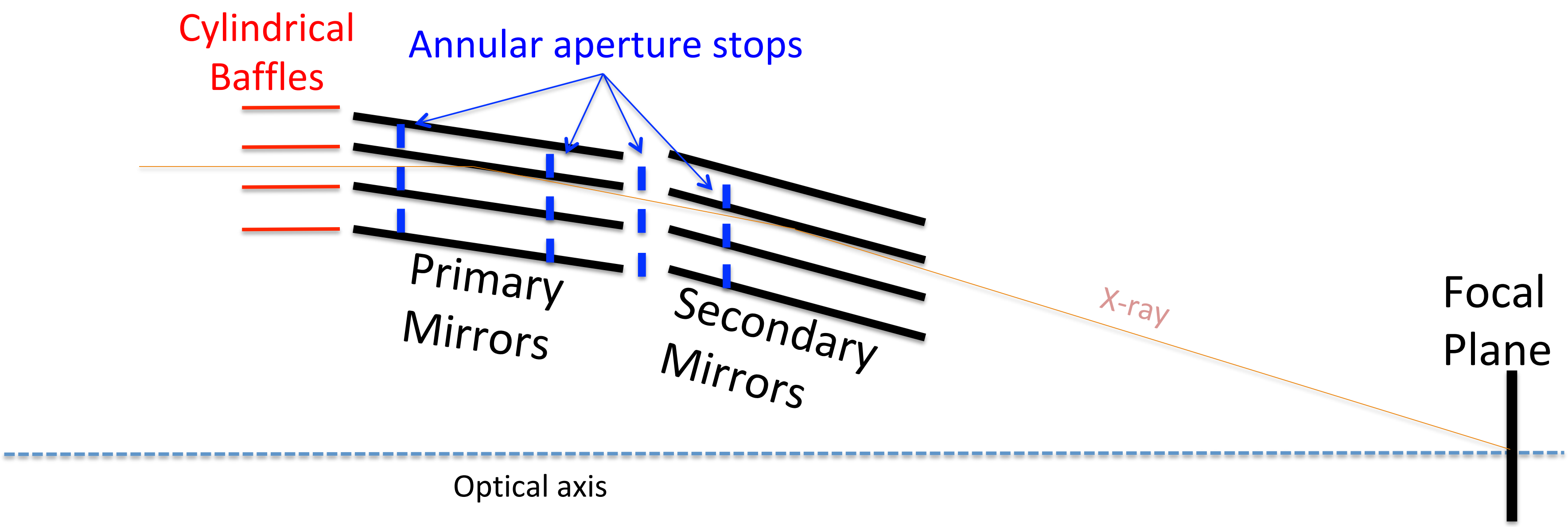
Engineering

Engineering of an X-ray Mirror Assembly

- **Take into account of the four technical elements and other technical knowledge and experience to arrive at a design that meets all requirements:**
  - Optical design, and stray light baffling,
  - Structural (aka mechanical) design,
  - Thermal design,
  - Gravity release consideration, and
  - Contamination control, etc.
- **Analyze the designs using finite element analysis and conduct tests and experiments to verify the analytical models.**

Optical Design and Stray Light Baffling

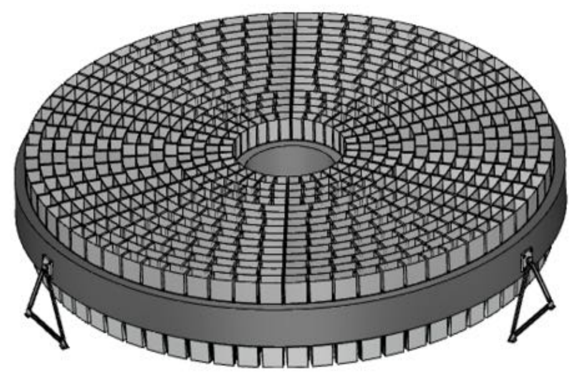
- **This technology is capable of implementing every conceivable optical design. For a mission like Athena, we would adopt a Wolter-Schwarzschild-Saha design, which is a traditional W-S design with optimized off-axis PSF.**
- **This technology can accommodate easily both external (cylindrical) baffle and internal (annular) baffle. For Athena, we will need only the external baffle.**



Two Ways to Build an Athena Mirror Assembly

- **The meta-shell approach**
  - The “native” approach
  - Advantages
  - Disadvantages

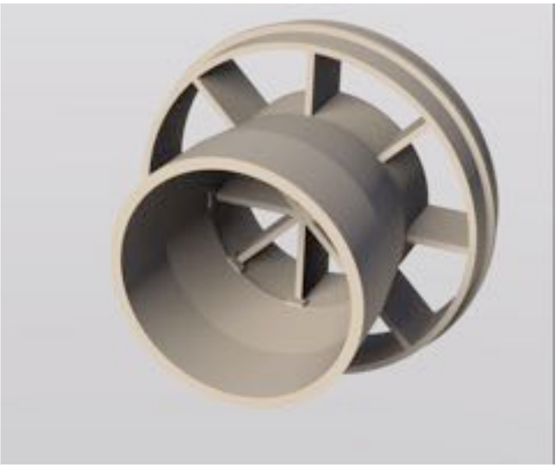
- **The stack approach**
  - The “traditional” approach
  - Advantages
  - Disadvantages

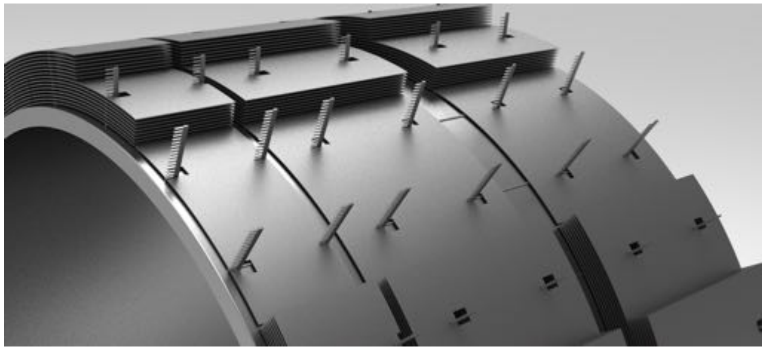


Credit: E. Breunig, J. Eder (MPE)

The Meta-Shell Approach

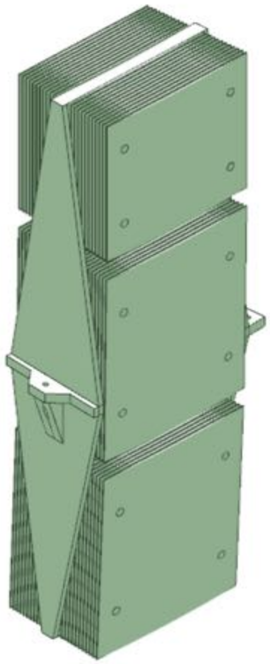
- **Performance Parameters**
  - 10 meta-shells, 28,466 mirror segments.
  - Mirror Assembly Mass: 895 kg, stray light baffles included.
  - Effective area (@1keV): 1.4 m^2, assuming simple iridium coating.
- **Advantages**
  - Very efficient use of aperture and mass; Meets Athena requirements without the need for any special coating.
  - Easy to test and integrate into the final mirror assembly.
- **Disadvantages**
  - Difficult to manage spares.





The Stack Approach

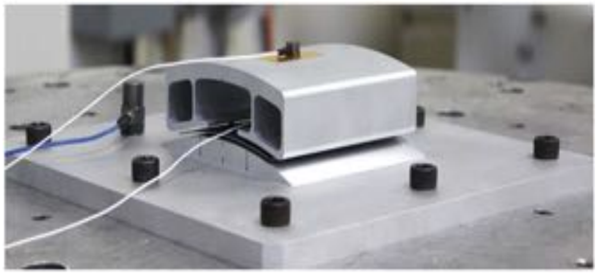
- **Performance parameters**
  - 582 stacks (or mirror modules); 29,568 mirror segments.
  - Mirror Assembly Mass: ~800 kg, stray light baffles included.
  - Effective area (@1keV): 1.2 m^2, assuming simple iridium coating.
- **Advantages**
  - Many identical and therefore interchangeable stacks/ modules, making it easy to manage spares.
  - Similarity to the Athena baseline approach.
- **Disadvantages**
  - Must use some special coating to meet effective area requirement.

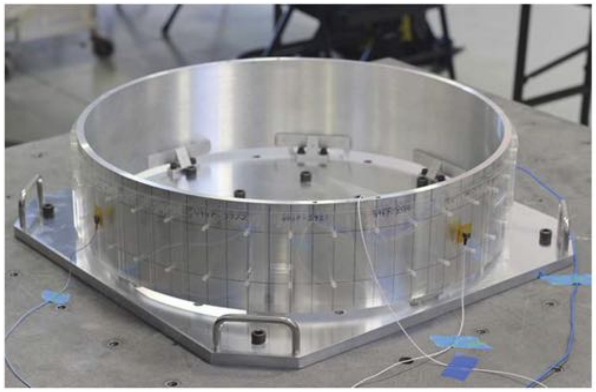


Mirror Stack or Mirror Module
Credit: J. Eder (MPE)

Structural Robustness: Testing

- **Test#1: a mockup for a stack of mirrors**
  - An aluminum base simulating structural shell.
  - A bonded silicon mirror segment.
  - An aluminum dummy mass.
- **Test#2: a mockup for a meta-shell**
  - Aluminum structural shell.
  - 3 layers (54 mirrors, 432 bonds) of mirrors.
  - 8 bonded flexures.
- **Test Results**
  - Both survived required random vibrations.
  - Both survived required quasi-static loads (12.3 g).



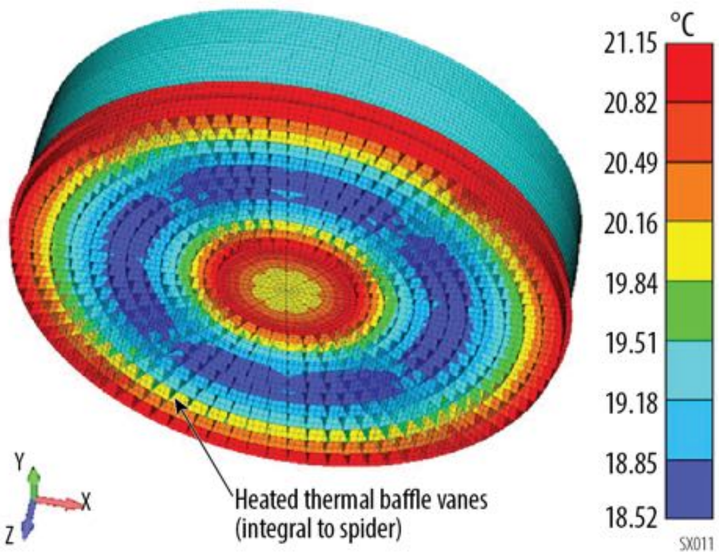


Thermal Engineering: Design

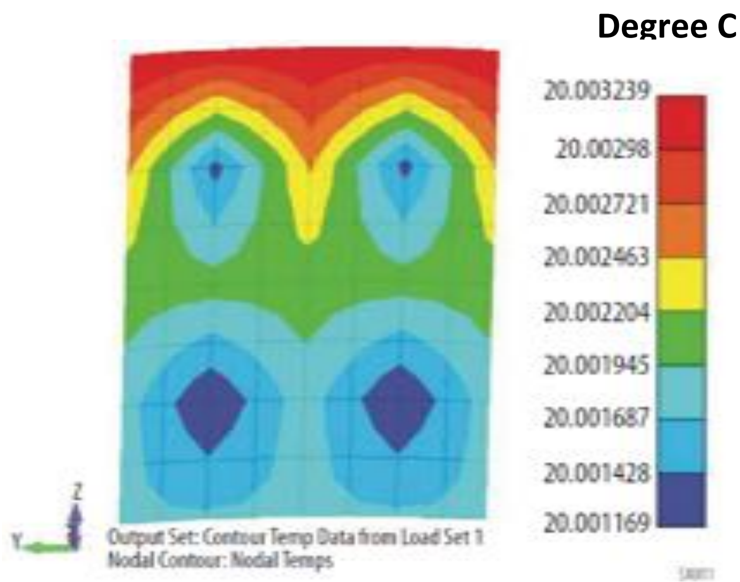
- **Excellent thermal properties of silicon**
  - Low thermal expansion, and
  - High thermal conductivity.
- **Each meta-shell is tightly coupled together thermally**
  - Radiation, and
  - Conduction: structural shell, spacers, and mirror segments.
- **Each mirror segment is heated two ways**
  - Radiation from thermal baffles and other objects in line of sight, and
  - Conduction from heaters attached to structural shell.

Thermal Engineering: Analysis

Thermal Gradient Map



Thermal Gradients on Mirror Segment



On-orbit thermal-induced PSF degradation: ~ 0.1 arc-seconds.

Gravity Release

- **Each mirror is supported by, and bonded to, 4 spacers, whose locations are optimized such that, when gravity disappears, the mirror has the smallest possible deformation.**
  - Optimization done by finite element analysis, and
  - Can be verified by measurement under gravity of a bonded mirror in different configurations.
- **Preliminary analysis shows that a net frozen-in error of ~0.1" HPD for a meta-shell with a diameter of 300mm.**

On-orbit gravity-release-induced PSF degradation: ~ 0.1 arc-seconds.

Production

Substrate Fabrication

- **Quantities**
  - 28,466 substrates of 702 different prescriptions.
- **Fabrication Steps**
  - Grinding, lapping, slicing, etching, polishing, thinning, slotting, trimming, etching redux, measurement, and IBF finishing.
- **Entire process completely understood**
  - At the 5” HPD (HEW) and 0.5 mm thickness level, and
  - Expecting higher than 90% yield.
- **Mass production process can be set up quickly**
  - Needing only commercial-off-the-shelf equipment and materials.
- **All mirror substrates needed for Athena can be manufactured**
  - In less than 2 years: 702 mirror segments can be made every workday.
  - With 1 year of preparation work: facilities setup, procurement of long-lead items, etc.

Coating

- **The 7 Steps to Achieve Non-distorting Iridium Coating**
  - Cleaning, oxidizing, stripping, coating of chromium and iridium, annealing, measuring, trimming of oxide layer using chemical etching (or ion-beam figuring).
- **The entire process has been exercised multiple times**
  - Understood at the 5” HPD (HEW) level.
  - Yield expected to be near 100%.
- **A production line can be set up in a matter of weeks**
  - Needing only COTS equipment and materials.
- **Coating of each substrate can be finished within a few hours of its fabrication.**

Production of Meta-Shells or Stacks

- **Alignment combs can be ordered from the semi-conductor industry**
  - Need about a total of 1,500 combs of 15 different prescriptions.
  - Many vendors are available to make them.
- **Stacks**
  - A total of ~700 stacks/modules are needed.
  - Several to many stacks/modules can be made every work day.
- **Meta-Shells**
  - A total of 10 meta-shells are needed.
  - They can be made in parallel. We expect that all of these meta-shells can be completed within 6 months of the completion of mirror fabrication and coating.

A Strawman Overall Schedule

- **T0 − T0+18 months (18 months): TRL-5 demonstration**
  - Build and test stacks or meta-shells with at least three layers of mirror segments.
  - These stacks or meta-shells are expected to meet every requirement: angular resolution, effective area, mass, vibration, thermal-vacuum, acoustic, and shock.
- **T0+18 − T0+42 months (24 months): TRL-6 demonstration and production preparation**
  - Build and test stacks or meta-shells that are specific to Athena design. They will meet all requirements.
  - Create production plan, organize teams, and prepare facilities.
- **T0+42 − T0+54 months (12 months): Production Preparation**
  - Hiring and training of workers.
  - Commissioning of equipment.
  - Conducting production test runs.
- **T0+54 − T0+84 months (30 months): Production and qualification, including both performance and environmental testing, of all stacks/meta-shells**
- **T0+84 − T0+96 months (12 months)**
  - Integration of stacks/meta-shells into the final mirror assembly.
  - Testing and calibration of mirror assembly.

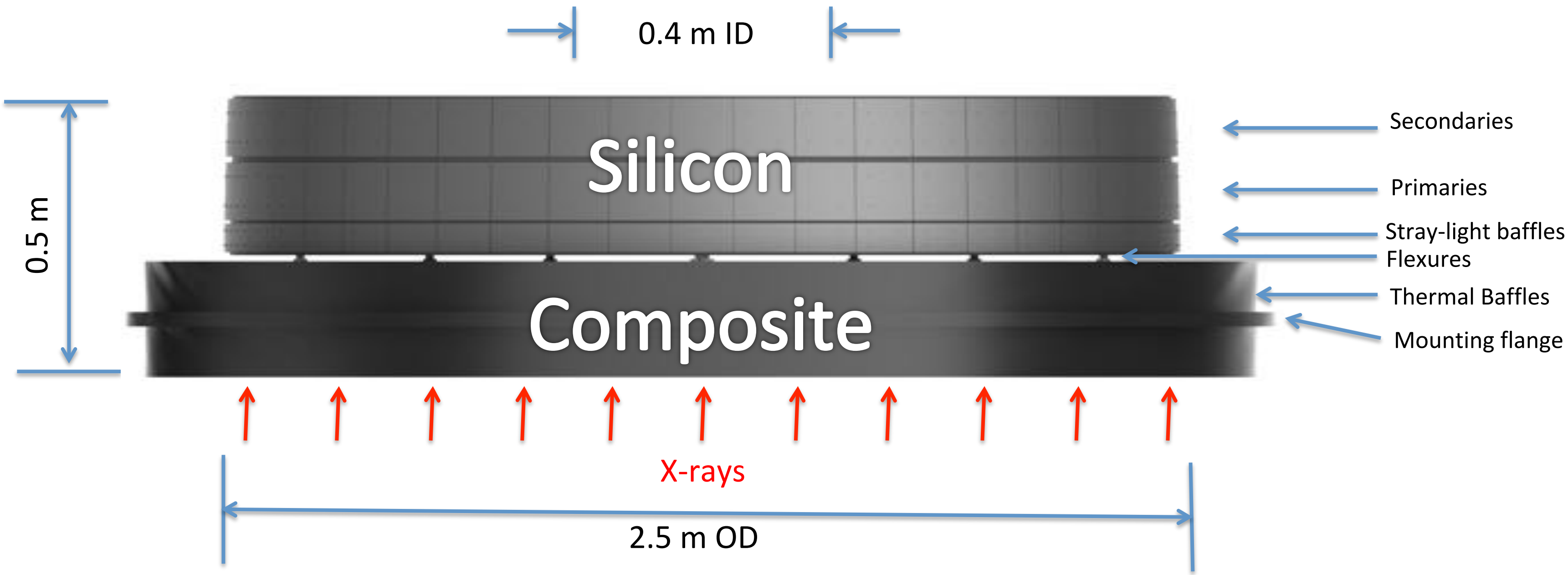
Top-Level Error Budget for a 5” Mirror Assembly

Source of Error		Allocation (arcsec HPD)	Determination & Verification
Optical Prescription	Diffraction contribution	0.20	At 1 keV, from calculation based on optical design.
	Geometric PSF (on-axis)	1.50	Wolter-Schwarzschild-Saha design.
Mirror Segment Fabrication	Mirror substrate	1.50	This number includes all possible errors of a pair of substrates. Based on normal incidence optical measurement and x-ray measurement.
	Coating	1.00	For a pair of mirrors. Based on normal incidence measurement of substrates before and after coating, and on x-ray measurement.
Meta-Shell Construction	Alignment	0.50	This number is for a pair of primary and secondary mirrors, including errors of spacer heights and mirror settling. Based on Hartmann measurement conducted with both visible light and x-rays.
	Bonding	0.50	This number for a pair of mirrors, including application of epoxy, its cure, and other effects related to bonding. Based on finite elment analysis and modeling of epoxy cure effect and on Hartmann measurement using x-rays.
Integration of Meta-shells to Mirror Assembly	Alignment	0.20	This number respresents the ability to orient and translate and verify the alignment of a meta-shell. Based on optical Hartmann measurement and fiduciary laser beams.
	Attachment	0.20	Based on optical alignment verification and end-to-end x-ray measurement.
Ground to Orbit Effects	Launch shift	0.50	Based on finite element analysis and modeling supported by empirical data of epoxy creep and long term stability.
	Gravity release	1.00	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.
	On-orbit thermal	1.00	Based on thermal modeling and analysis.
On Orbit Performance (RSS)		**2.89**	This is the on-axis performance of XMA on orbit. Add effects of jitter and detector pixillation to get the final obervatory-level PSF.

Summary

- **Technology**
  - Can definitely meet the 5” requirement, likely to achieve the 3” goal.
  - TRL-4 done for a 5” telescope. Work continues to achieve ever-better angular resolution.
  - TRL-5 work in progress, to be completed by December 2019.
  - TRL-6 work to be completed by December 2019: a meta-shell with 288 mirror segments for OGRE, a sounding rocket experiment led by Randy McEntaffer of Penn State Univ.
- **Engineering**
  - Preliminary (or generic) engineering indicates there is no show stopper.
  - Further detailed engineering design and analysis specific to Athena are needed.
- **Production**
  - This technology is capable of massive parallel production, and should meet any reasonable schedule of any spaceflight mission.
  - We expect that a mirror assembly can be made for Athena within 5 years of authorization to proceed, say, 2021 or 2022.

Conception of an Athena Mirror Assembly



28,466 mirrors → 10 meta-shells → 1 assembly

Mass: ~895 kg **Heater Power: ~1,200 W**

Eff. Area@1keV: 1.4 m^2 with traditional Ir coating