X-ray Optics for Lynx

William W. Zhang & Ryan S. McClelland

On behalf of

The Next Generation X-ray Optics Team

NASA Goddard Space Flight Center

NASA Marshall Space Flight Center

Next Generation X-ray Optics 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], R.S. McClelland[1], H. Mori[2], A. Numata[1], T. Okajima, L.G. Olsen, R.E. Riveros[2], T.T. Saha, M.V. Sharpe[1], P.M. Solly[1], W.W. Zhang

NASA Goddard Space Flight Center

[1] Stinger Ghaffarian Technologies, Inc.

[2] University of Maryland, Baltimore County

J.M. Carter, J.A. Gaskin, W.D. Jones, J.J. Kolodziejczak, S.L. O'Dell

NASA Marshall Space Flight Center

Personnel Roles

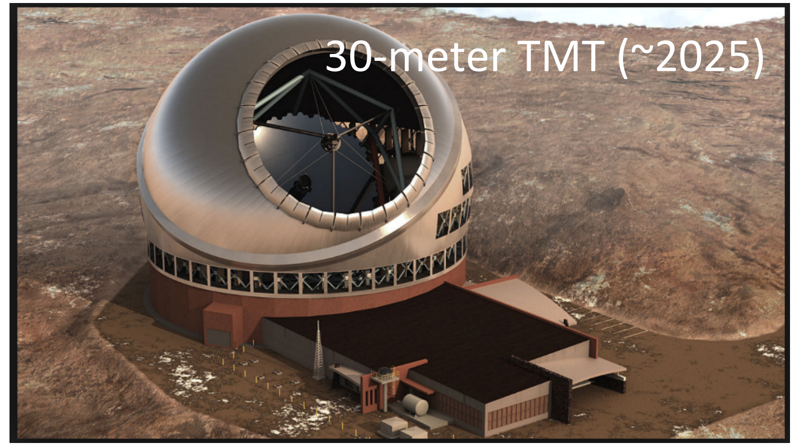
- Principle Investigator: **William Zhang**
- Chief Telescope Engineer: **Ryan McClelland**
- Telescope Scientist: **Kai-Wing Chan**
- Optical Engineer/Designer/Analyst: **Timo Saha**
- Mirror Fabrication Engineer: **Raul Riveros**
- Process and Automation Engineer: **Michael Biskach**
- Coating Scientist: **Takashi Okajima**
- Alignment and Bonding Engineer: **James Mazzarella**
- Structural/Optical Analyst: **Peter Solly**
- Thermal Engineer: **Joseph Bonafede**
- Performance Test Scientist: **Stephen L. O'Dell**

Presentation Outline

- **Introduction**
  - Lynx optics challenge in context
- **Technology**
  - Substrate fabrication
  - Coating
  - Mirror alignment and bonding
- **Engineering**
  - Construction of meta-shells
  - Structural and thermal design & analysis
  - Integration of meta-shell into mirror assembly
- **Technology Demo & Mirror Assembly Production**
  - Tech demo between now and Decadal
  - Considerations for mirror assembly production

Lynx Optics Challenge in Context

Mirror Area: 19 m^2

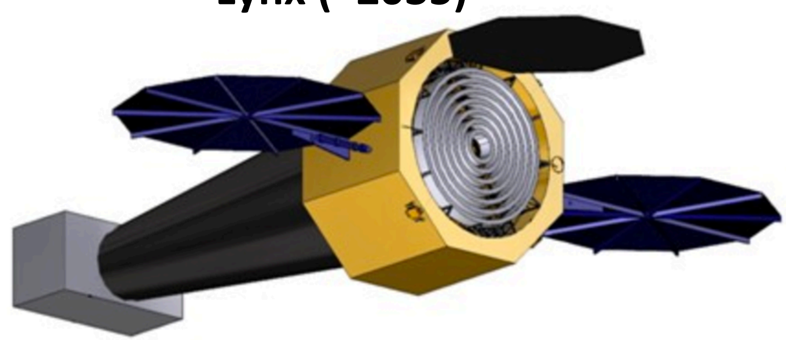


Mirror Area: ~700 m^2

Chandra (1999)

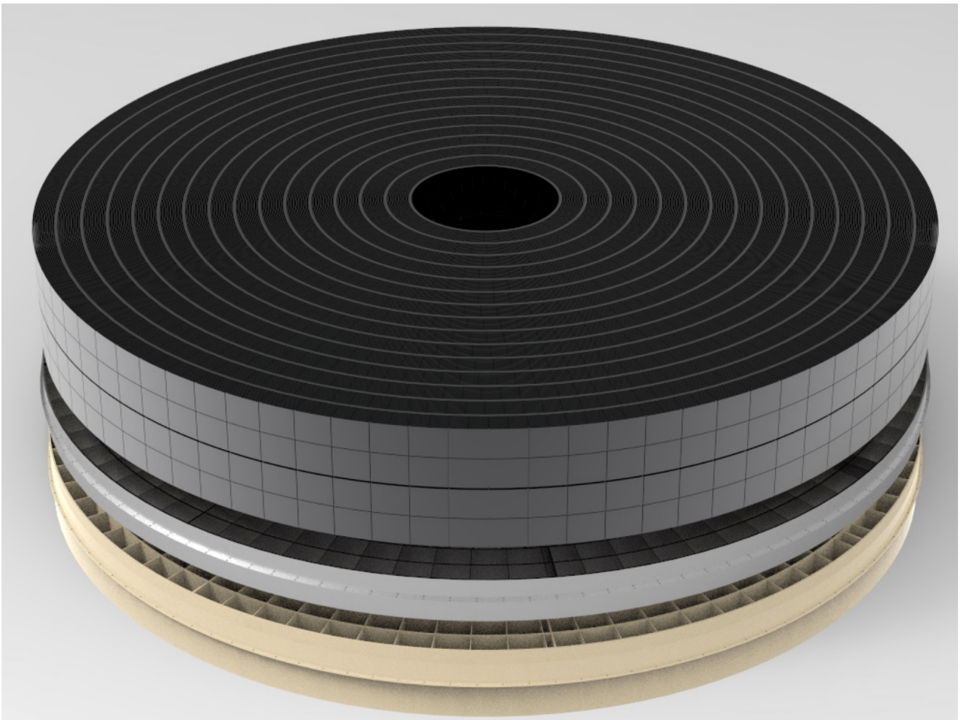
Mirror Area: 19 m^2

Lynx (~2035)



Mirror Area: ~600 m^2

What a Mirror Assembly Looks Like?



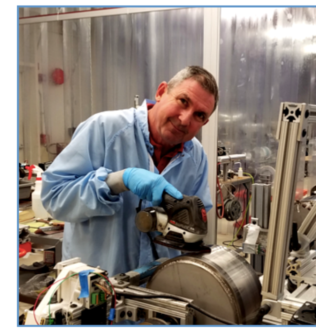
- **Angular resolution**
- **Effective area** or **Mass**
- **Production cost** and **schedule**

- **~50,000 mirror segments → 15 meta-shells → 1 mirror assembly**
- **Thermal pre-collimators, stray light baffles, heaters, etc.**

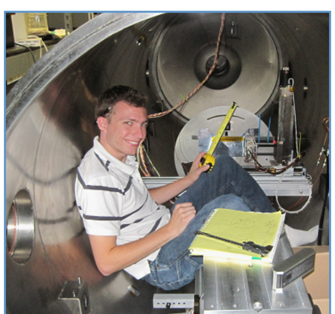
Fabrication of Mirror Substrates

Riveros

Kearney



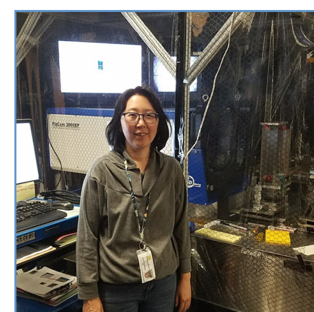
Biskach



Allgood

Sharpe

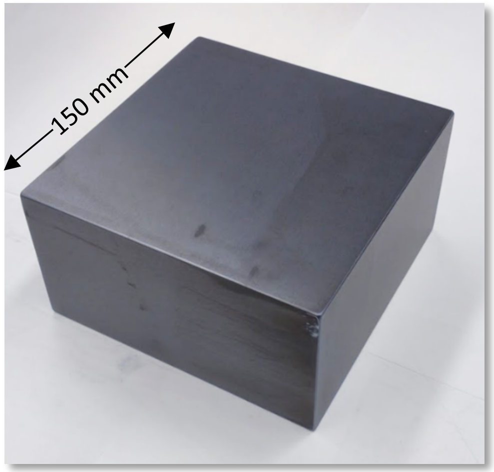
Numata



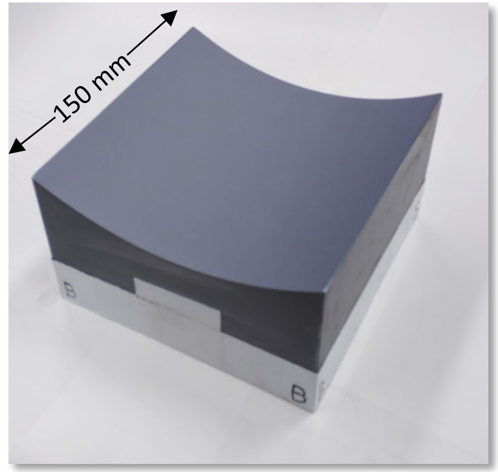
Mirror Substrate Fabrication

- **Material: mono-crystalline silicon**
  - Free of stress
  - Low density: 2.35 g/cm^3
  - High thermal conductivity: 150 W m^{-1} K^{-1}
  - High elastic modulus: 130 – 188 Gpa
  - Low thermal expansion: 2.6 ppm/K
  - Commercial availability
  - Best studied and understood material
- **Fabrication process: polishing**
  - Grinding, lapping, slicing, acid etching, full-aperture polishing, & sub-aperture polishing , etc.
  - Best possible figure and finish quality
  - Mass production and robotics to minimize cost

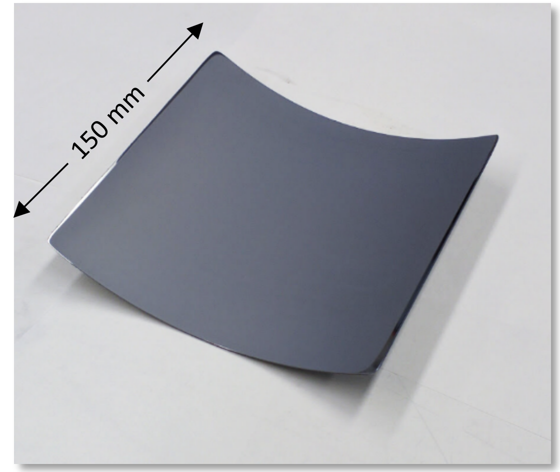
Fabrication Steps



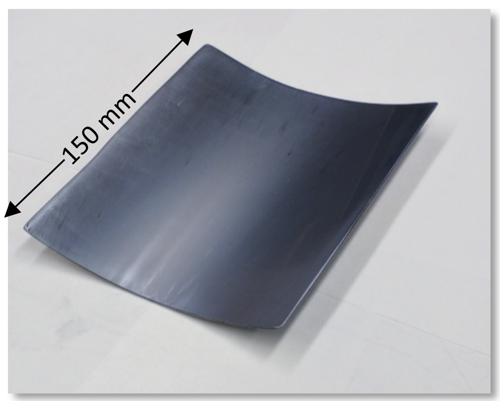
Monocrystalline silicon block



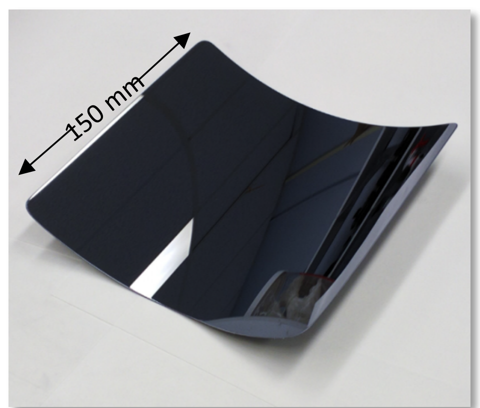
Conical form generated



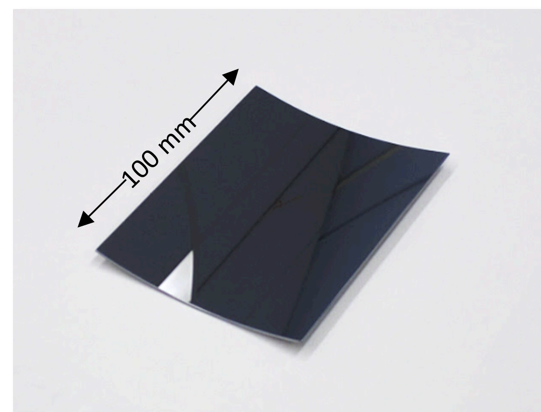
Light-weighted substrate



Etched substrate



Polished mirror substrate



Trimmed mirror substrate

Status of Substrate Fabrication

Slope Power Spectral Density

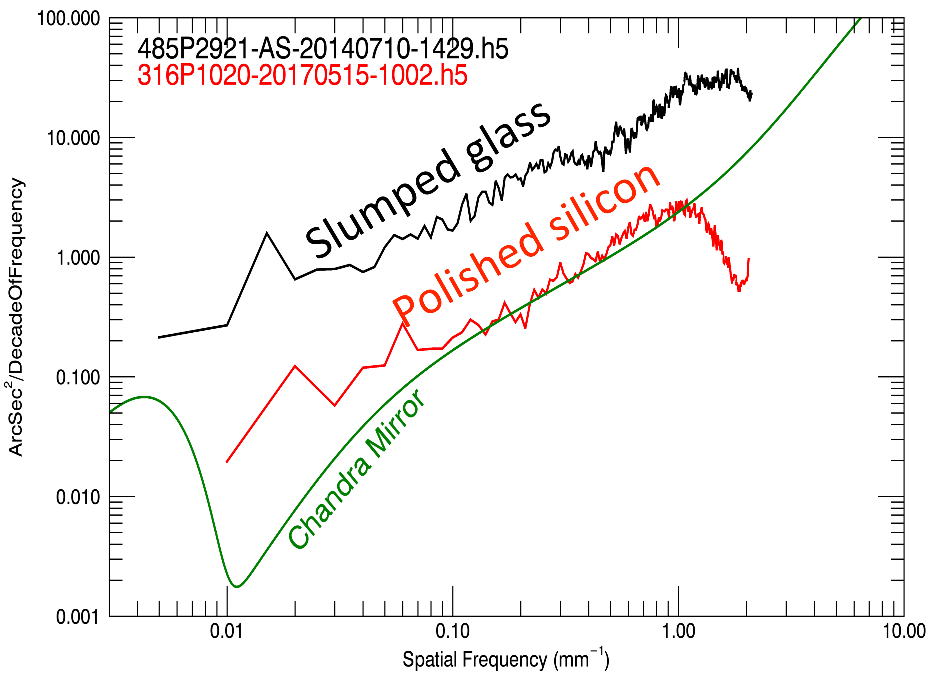
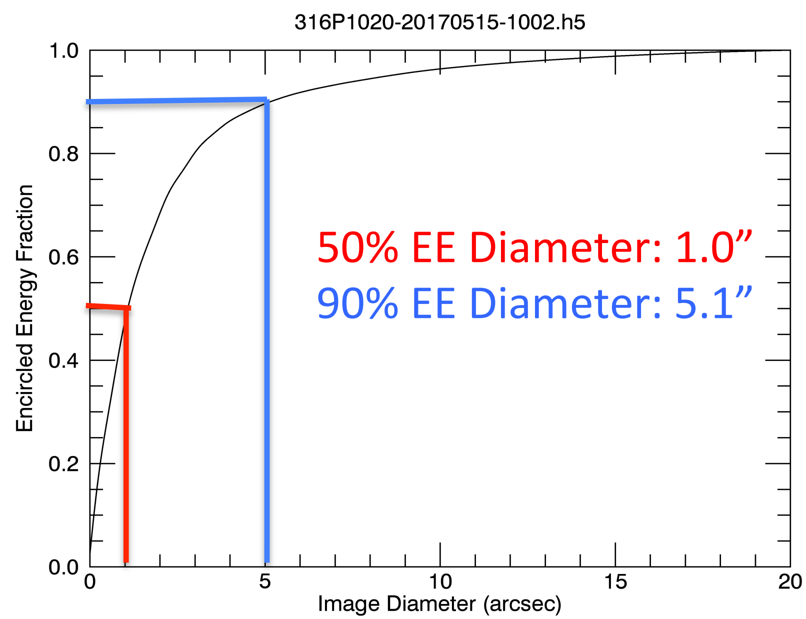


Image Performance Prediction (2 reflections)



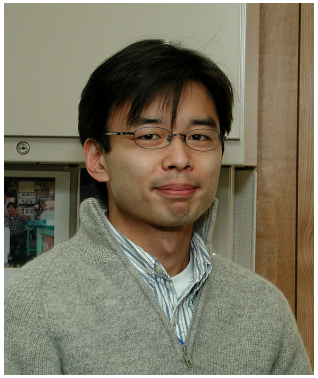
Substrate Fabrication Summary

- **Can realize any optical design**
  - Wolter-I
  - Wolter-Schwarzschild
  - Or any other: equal-curvature, polynomial, etc.
- **Can make substrates better than Chandra's**
  - Better micro-roughness → better-behaving PSF
  - Thickness from 0.5 to 1.5mm (cf. Chandra's 10-20mm)
- **Use no special or custom equipment**
  - All equipment are commercial off the shelf.
  - All tooling can be made in ordinary machine shops.
- **High throughput and low cost**
  - Fabrication process is highly amenable to automation & mass production

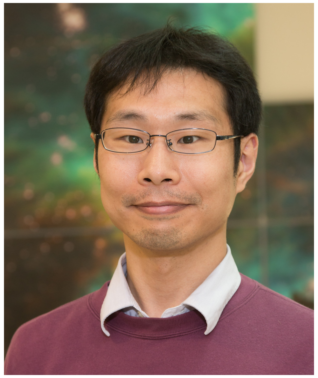
Coating

Chan

Okajima



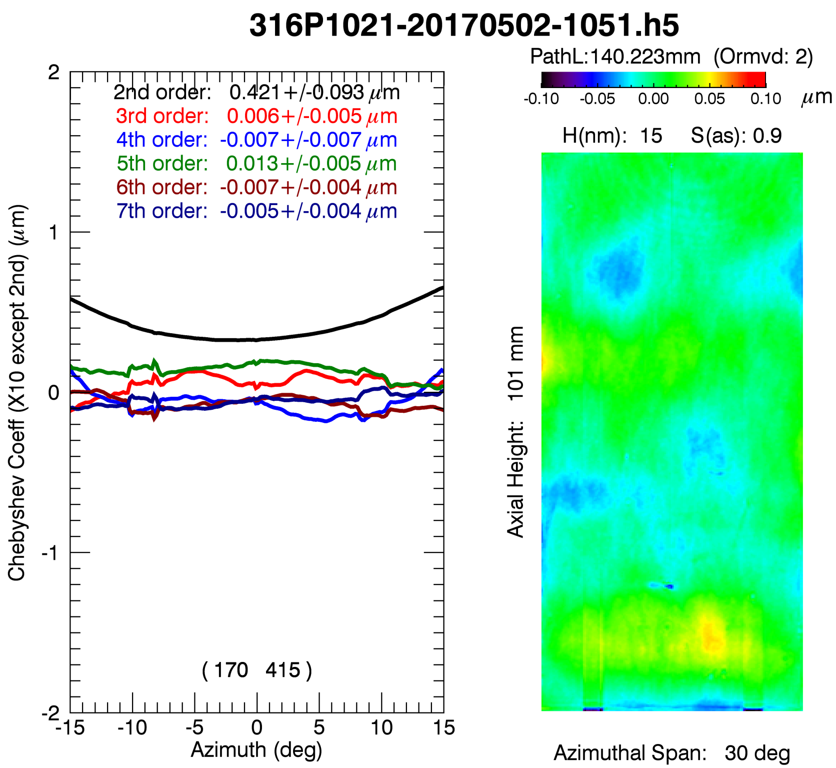
Mori

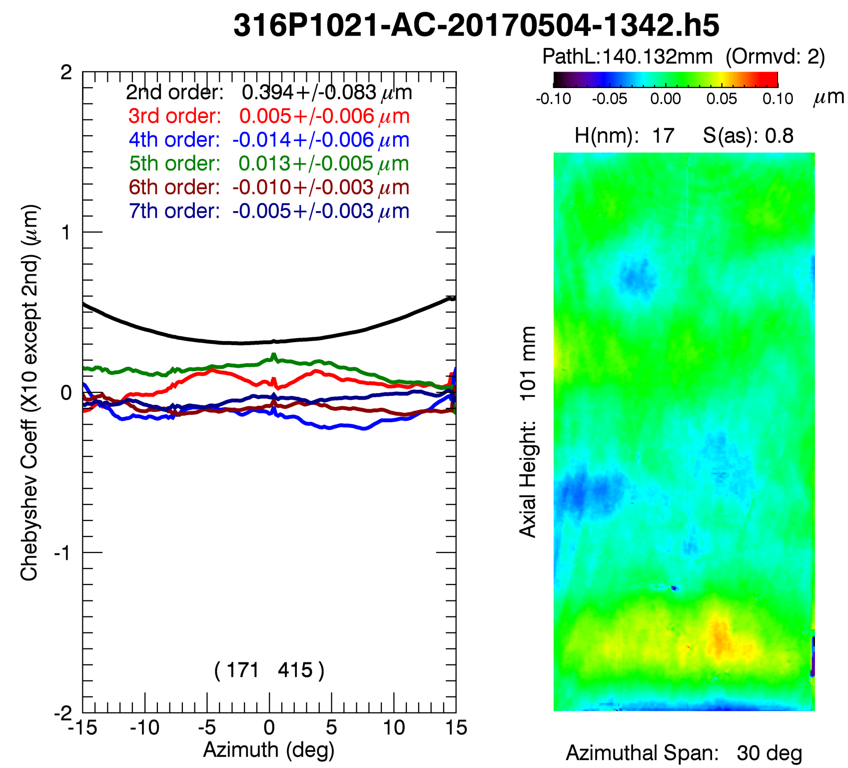


Coating

- **Coating is an essential part of a strategy to meet effective area requirements**
  - A good coating is a necessity, not an option
- **Noble metal coating**
  - **Au:** Low stress ←→ Low reflectivity
  - **Pt:** Medium stress ← → Medium reflectivity
  - **Ir:** High stress ← → High reflectivity
- **Other possibilities**
  - An iridium layer plus an overcoat of B_4C or Al_2O_3

Effect of 15nm Pt Coating





P-V Sag change 54 nm → 0.32" in HPD change

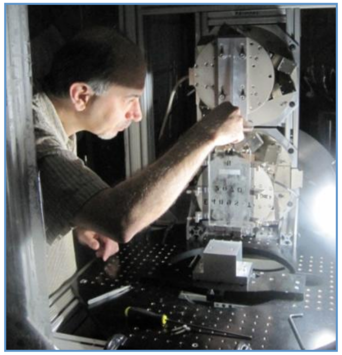
Solutions being Pursued at GSFC

- **Balance front and back**
  - Investigating Pt coating now
  - If successful with Pt, will investigate Ir
- **Balance thin-film stress on the front with SiO_2 stress on the back**
  - Coatings typically have compressive stress
  - SiO_2 also has compressive stress. Its growth can be controlled to an accuracy of 1 nm.
- **Polish a figure error in the substrate that will cancel distortion caused by coating stress, if the effect of coating stress is highly repeatable & stable.**

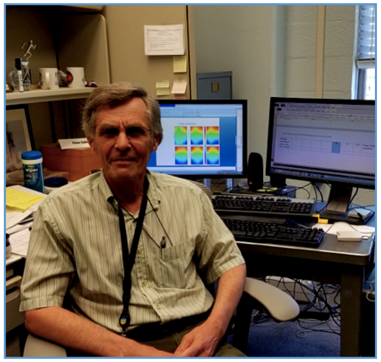
Alignment and Bonding

Chan

Mazzarella



Saha

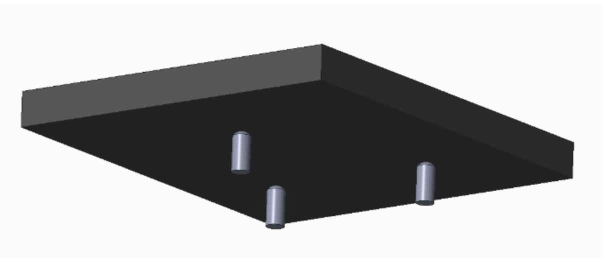


Approach to Alignment & Bonding

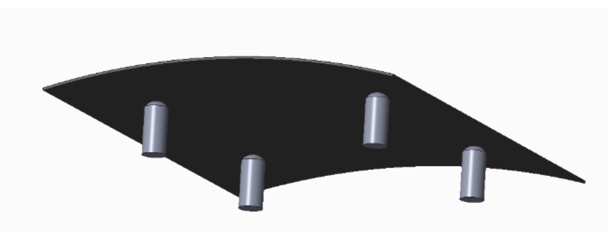
- Use **kinematic mount** to minimize/eliminate distortion to mirror segments
- Use **finite element analysis** to optimize locations of supports
- Use epoxy as **adhesive only**, not as a filler of any space that is not precisely controlled
- Use **gravity**, the most repeatable force, as the nesting force

Minimal Constraints

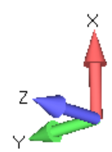
- **Three spacers or posts fully determine the orientation of a flat mirror:**
  - pitch, yaw, & x by gravity
  - roll, y, and z by friction



- **Four spacers or posts fully determine the orientation of an X-ray mirror:**
  - pitch, yaw, x, and y by gravity
  - z and roll by friction



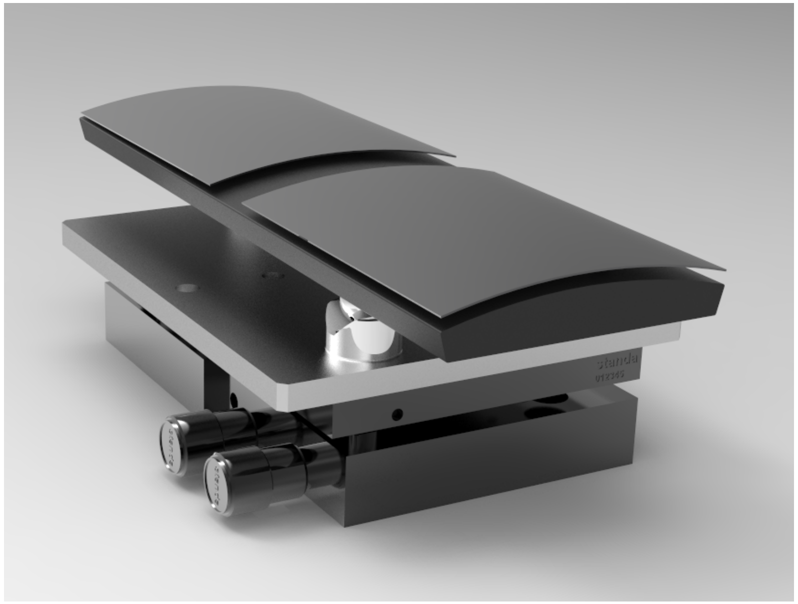
- **Use vibration of optimal frequency and amplitude to overcome friction**



Proof of Concept

- **Placement repeatability**
  - The same mirror from placement to placement
  - From one mirror to another of the same prescription
  - Stability over long periods of time: ~10 hours
- **Precision machining of posts**
  - Current precision at 25 nm, limited by metrology
  - Enables sub-arcsecond mirrror alignment
- **Bonding mirror with epoxy**
  - Preserves alignment: no indication of alignment shift
  - Preserves figure: only localized distortions due to epoxy cure stress

Proof of Concept Module



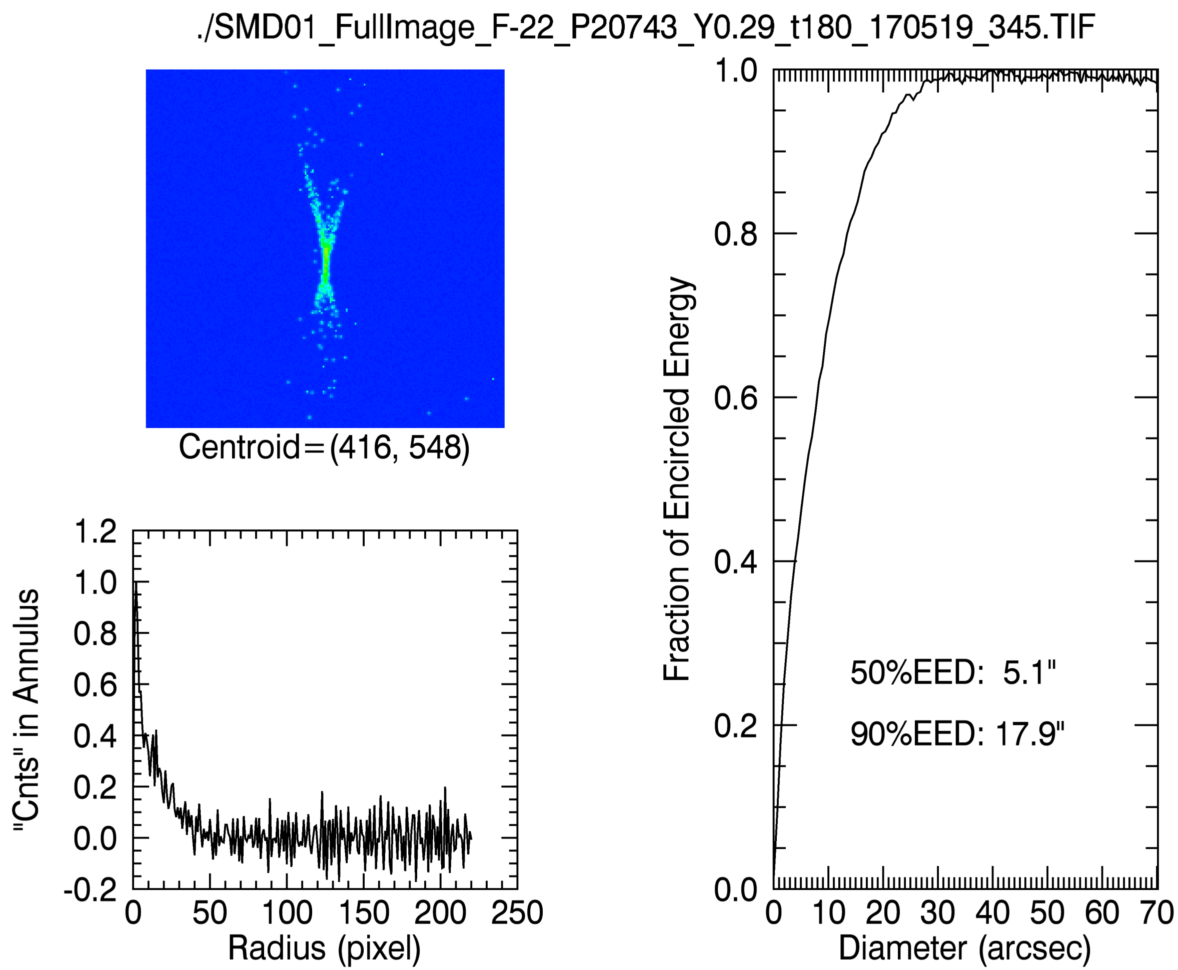
Accomplished as of May 2017

Single pair of mirrors aligned, bonded, and X-ray tested.

Expected to be accomplished by December 2017

Multiple pairs of mirrors aligned, bonded, and X-ray tested.

X-ray Test Result

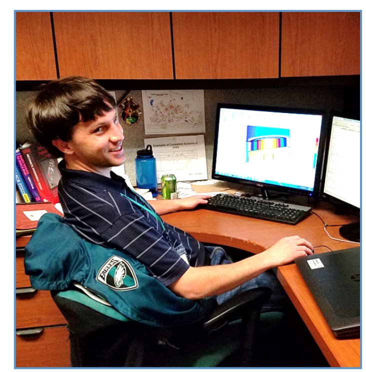


Engineering: Structural, Thermal, & Systems

McClelland

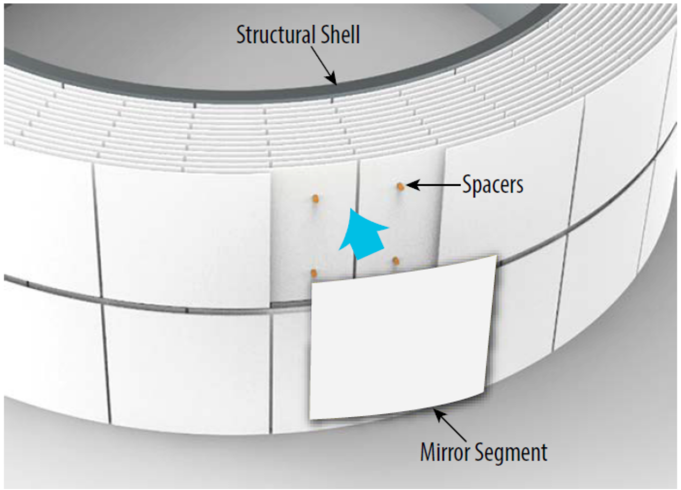
Bonafede

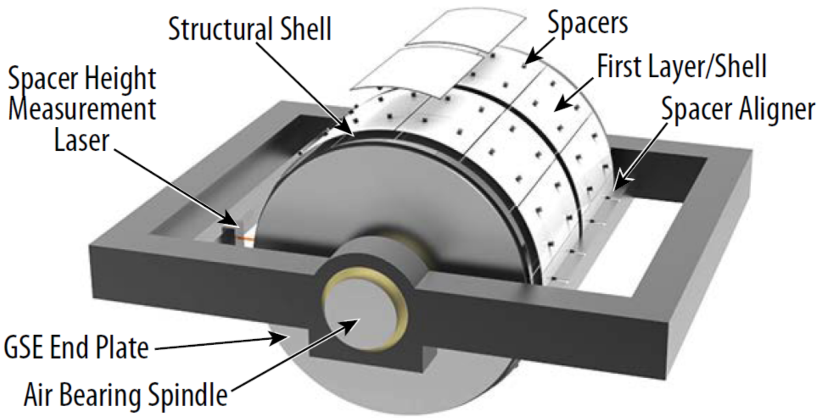
Solly



Meta-Shell Approach

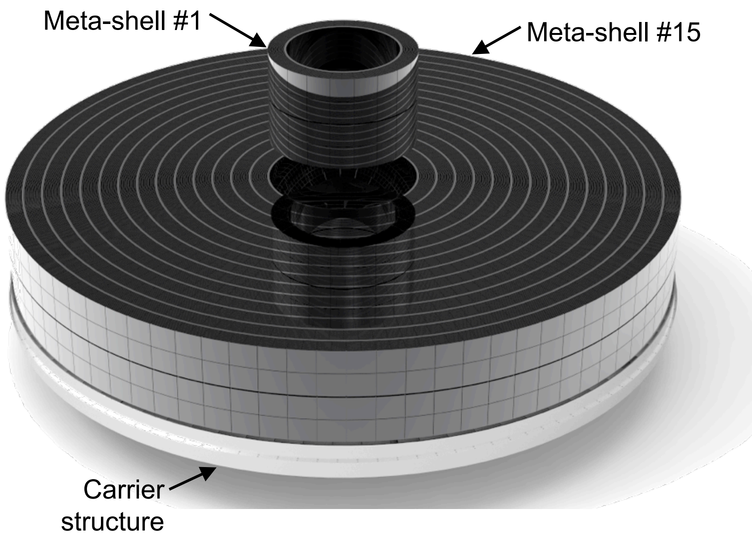
- **Meta-shell integrates many four spacer mounted segments**
  - Interlocking layers of mirror segments bonded onto a central structural shell (silicon)
  - Mirrors are cantilevered off structural shell similar to NuSTAR
  - Brick-like buildup spreads the load
- **Once complete, meta-shell is similar to a full shell with an order of magnitude more collecting area**
  - Structurally stiff (all silicon)
  - Rotationally symmetric
  - Insensitive to tilt
  - Leverage Chandra and XMM-Newton heritage
- **Integrated on a precision air bearing**
  - Creates an optical axis reference
  - Post heights determined by Hartmann test
  - Bonded in distortion 0.05" HPD

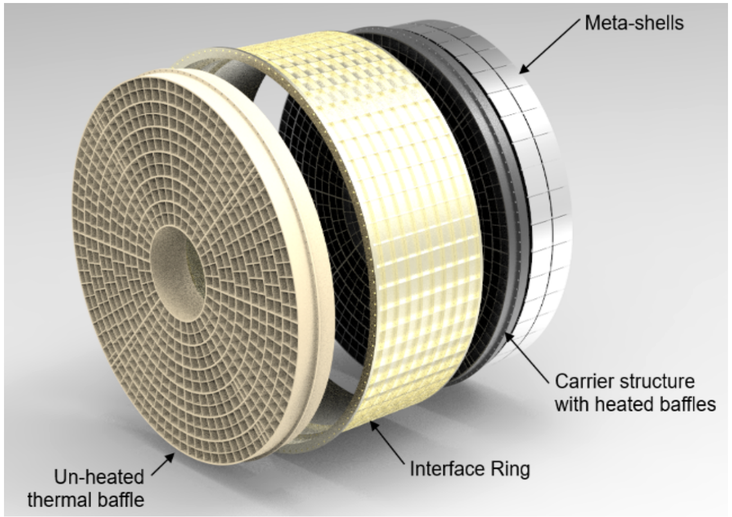




Mirror Assembly

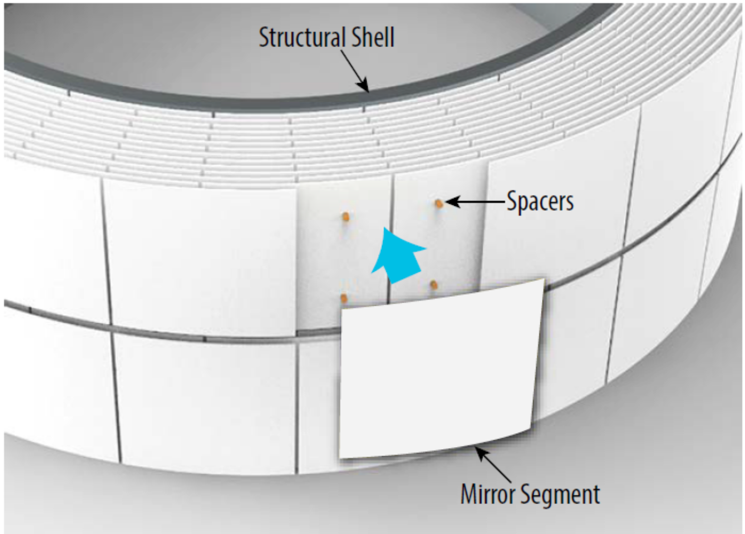
- **Multiple concentric meta-shells co-aligned and mounted into a carrier structure**
  - Similar to Chandra (CAP) and XMM-Newton (Spider)
  - Aluminum structure (or CFRP)
  - Co-align and bond meta-shells using Chandra techniques (CDA with retro-reflecting flat, etc)
  - Chandra-like flexure mount allows for mechanical isolation
- **Heated stray-light / thermal baffles integral to carrier structure (Aluminum)**
- **Mount within Interface Ring that provides interface to telescope/ spacecraft (Aluminum)**
- **Un-heated thermal baffles (G10)**

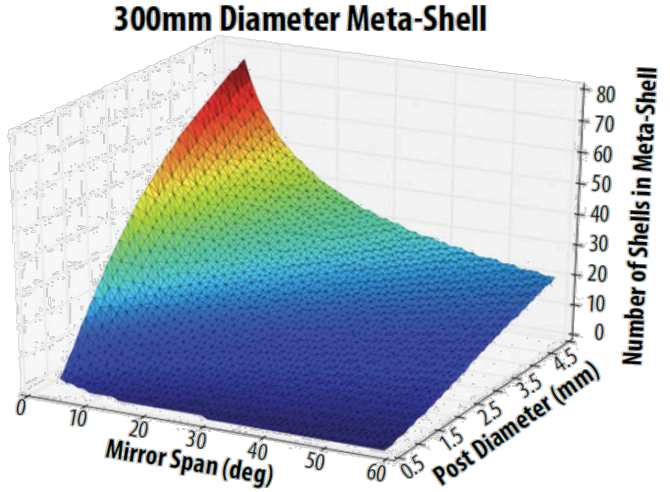




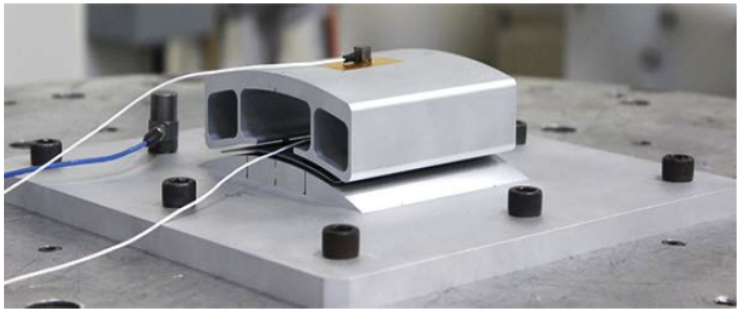
Structural Analysis

- **Analysis and test show weak point is innermost bond**
- **Bond stress is determined by:**
  - Bond / spacer diameter
  - Number of segments around the circumference, i.e., number of bonds per layer
  - Number of layers
- **Mathematic model of bond stress developed**
  - Determines feasible meta-shell designs
  - Verified by detail FEA and coupon tests
- **Deterministic method to derive all meta-shell design parameters**

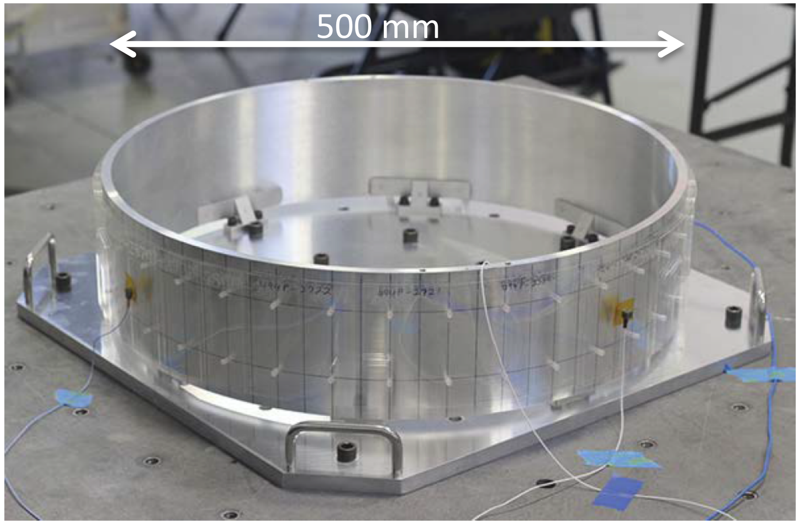




Prototype Environmental Testing

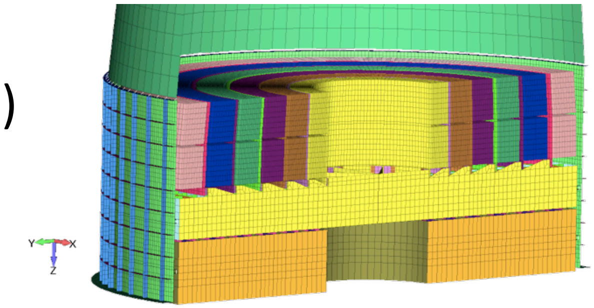


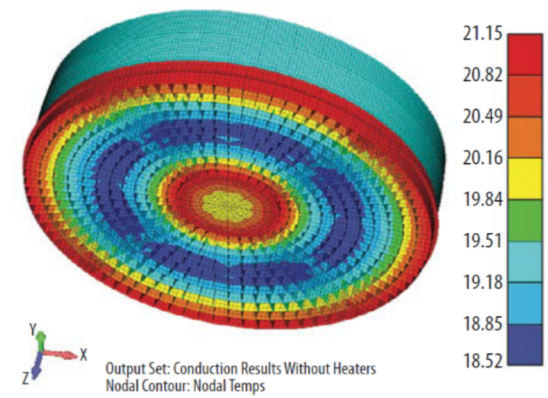
- **Developed conservative preliminary requirements**
  - Quasi-static design loads for IXO CLA with 2.0 MUF
  - Random loads from GEVS
  - Shock loads from Falcon 9
- **Cantilevered mass prototype**
  - Dummy mass simulates layers of mirrors
  - Single silicon segment with four spacer bonds
  - Survived required random vibration
  - Survived required shock (200 g)
  - Silicon is strong (if treated properly), has good damping, and bonds well
- **Meta-shell mechanical mock-up**
  - Aluminum and glass meta-shell
  - Bonded flexures
  - 3 layers (54 mirrors, 432 bonds)
  - Survived required random vibration
  - Survived required quasi-static load (12.3 g)

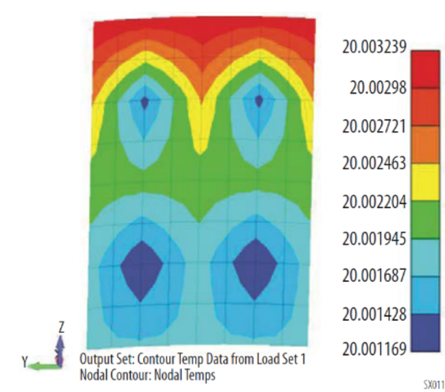


Thermal Control

- **Follow Chandra approach**
  - Optics operate at 20°C (baseline, colder possible)
  - Heat lost to cold space is replaced by heaters surrounding the optical cavity
  - View to cold space is limited by thermal baffle vanes (heated and un-heated)
- **Design verified by preliminary Structural Thermal Optical Performance (STOP) analysis**
  - Thermal model predicts temperatures
  - Temperatures mapped to structural FEM
  - Distortion predictions ray-traced
- **Low CTE and high thermal conductivity of Silicon result in low thermal sensitivity**
  - Minimal gradients over a mirror segment
  - Current result 0.16” HPD, room for optimization
  - Best STOP result from IXO 6.6” HPD with glass

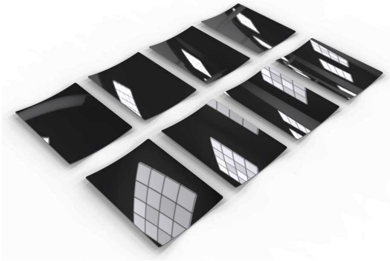


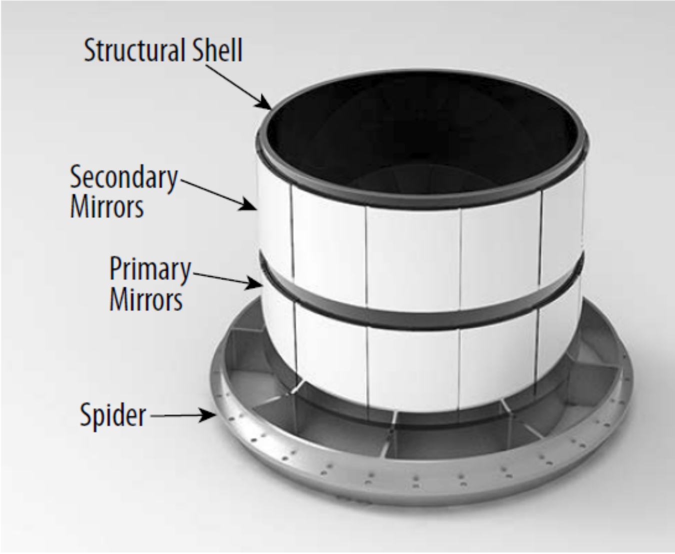




Summary

- **Meta-shell approach addresses X-ray mirror needs for Lynx**
  - Advantages of full shell optics but with an order of magnitude more collecting area
- **Preliminary structural, thermal, and optical analysis completed to mature the system design**
  - Shows 0.5” mission is feasible
- **Prototype load testing demonstrates the meta-shells are robust**
- **Development continues: design, analysis, testing**





Technology Demonstration and Production of a Mirror Assembly

Problem and Solution

- **Lynx's mirror assembly presents a significant challenge**
  - Technical: angular resolution & effective area & mass
  - Schedule: production time must be < 10 yrs
  - Cost: total assembly cost ~$500M (RY)
- **The meta-shell approach offers a potentially very attractive solution**
  - Highly probability to meet angular resolution and effective area requirements
  - Uses COTS and traditional techniques, equipment, etc.
  - Highly amenable to compartmentalization and mass production
  - Highly amenable to cost and schedule risk reduction

Between Now and Decadal Time

- **Empirically demonstrate that mirror segments meeting (or close to meeting) requirements can be made**
  - Repeatedly (high yield),
  - Quickly (production rate), and
  - Cost effectively
- **Build and test small mirror modules**
  - Basic alignment & bonding procedure is sound & efficient
  - They meet performance and environmental requirements
- **Build and test reasonably-defined meta-shells**
  - Meet both performance and environmental tests
  - Reach **TRL-5** by 2020
  - Show a clear path to **TRL-6** once the observatory is defined with sufficient fidelity

Mirror Assembly Production (1/2)

~**50,000** mirror segments

→ ~**15** meta-shells

→ **1** mirror assembly

~**8** mirror fabricators

→ ~**4** meta-shell makers

→ **1** integrator/tester

Distributed production → Competition → Cost/Schedule risk reduction

Mirror Assembly Production (2/2)

- **Technology team:** Technical oversight, Prompt identification of and solution to technical problems
- **Prime contractor**: Overall responsibility, Systems engineering, I&T, Selection of sub-contractors
- **Meta-shell sub-contractors:** production, and delivery of meta-shells
- **Mirror fabrication sub-contractors:** production and delivery of mirror segments

Acknowledgements

This work has been funded by NASA

through

ROSES/SAT and ROSES/APRA.