Highlights of the Workshop
Optics for the X-ray Surveyor

Mark Schattenburg

Space Nanotechnology Laboratory
Kavli Institute for Astrophysics and Space Research

X-ray Surveyor STDT Bi-Weekly Meeting

May 25, 2016

SPACE NANOTECHNOLOGY LABORATORY
MIT KAVLI INSTITUTE FOR ASTROPHYSICS AND SPACE RESEARCH

Massachusetts Institute of Technology

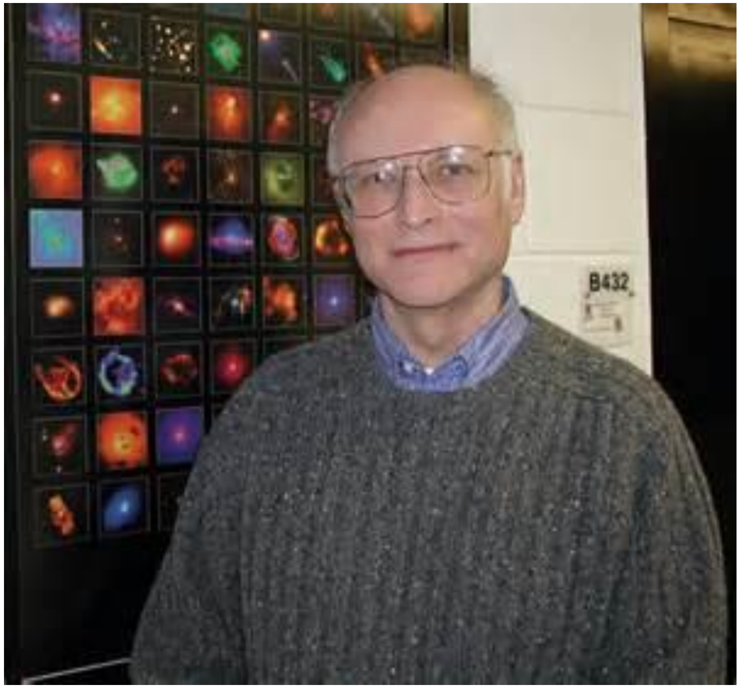
Workshop Details

- Community event (*not NASA STDT sponsored*)
- University of Maryland, March 28-29
- 40+ participants
  - NASA GSFC, MSFC, Ames, HQ
  - Harvard-SAO, MIT, U. Iowa, U. Alabama, Northwestern U.
  - Lawrence Livermore National Laboratory
  - RXO, Inc., Izentis, LLC, Bauer, Inc.
- 21 Presentations, 3 posters, 5 hours of moderated discussion
- Corporate sponsors:
  - Bauer, Inc., Izentis LLC

Organizing Committee

- Ryan Allured (Harvard-SAO)
- Mikhail Gubarev (NASA MSFC)
- Randy McEntaffer (U. Iowa)
- Paul Reid (Harvard-SAO)
- Mark Schattenburg (MIT)
- Mel Ulmer (NW)
- Will Zhang (NASA GSFC)

With inspiration provided by …



Leon P. Van Speybroeck (1935 – 2002)
Chandra X-Ray Observatory
Telescope Scientist

Special thanks to …

Richard Mushotzky of the University of Maryland for providing meeting space and logistical support

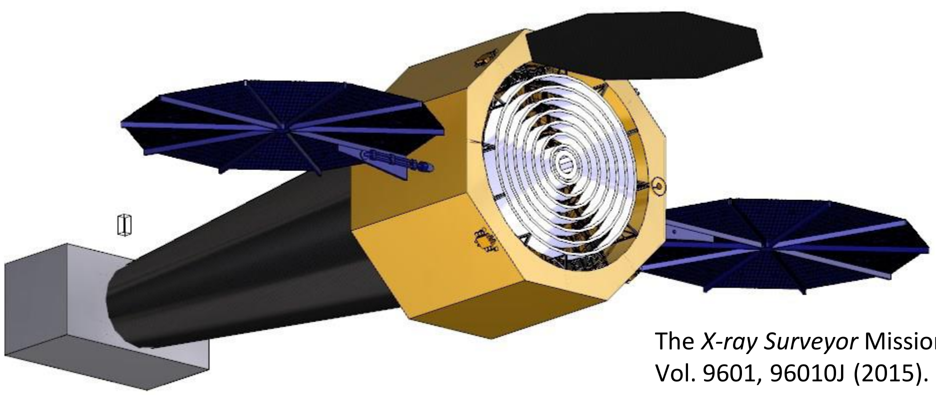
Workshop Goals

- Provide a forum to kick-start discussion by bringing together leading x-ray telescope engineers and scientists
- Look for ways to strengthen the community
- Review state-of-the-art of x-ray mirror technology
- Enumerate and describe potential approaches and produce straw man error budgets
- Spotlight issues shared by all approaches
- Find synergies and potential collaborations between approaches and participating institutions
- Identify technology gaps
- Discuss potential technology demonstrations for the Decadal Review

The workshop avoided generating detailed plans, specific recommendations or in-depth analysis. That is the role of the STDT.

Notional XRS Mirror Requirements

Diameter	3 m
Focal length	10 m
On axis HP diameter (1 keV)	0.5 arc sec
Design	Wolter-Schwarzshild
FOV diameter (<1 arc sec)	15 arc min
Mirror shells	~300
Mirrors (segmented design)	10,000 to 50,000
Effective area @ 1 keV (mirror only)	~2.5 m^2
Nominal bandwidth	0.1 - 10 keV



The *X-ray Surveyor* Mission: A Concept Study, Jessica A. Gaskin, et al., Proc. SPIE Vol. 9601, 96010J (2015). Also thanks to Will Zhang and Ryan Allured.

Have Cake and Eat Same

Chandra Telescope

High resolution, small area

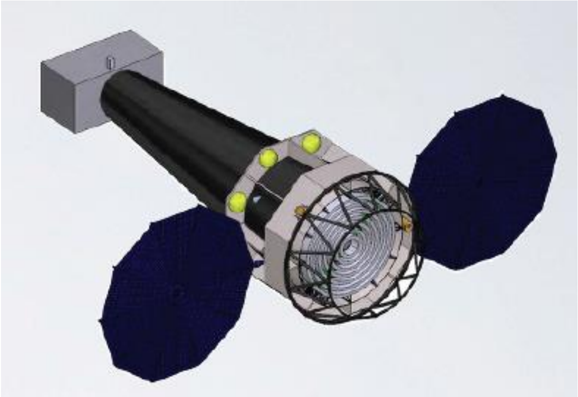
+

NuSTAR Telescope

Low resolution, large area

=

X-ray Surveyor



High resolution, large area

Can we achieve both high resolution and large area?

XRS Optics are **Qualitatively Different** than Chandra's

- XRS calls for ~30X more area than Chandra, but with same resolution (0.5")
- The best thin shell mirrors today have a resolution **20x worse** than this goal!
- No offence to our Chandra veterans, but the Chandra mirrors were trivial to make in comparison to XRS mirrors. Remember Chandra had:
  - Massively thick mirrors!
  - All low CTE materials!
  - Beefy metering structure!

Thin shell mirrors suffer from exquisite sensitivity the environment:

- Huge gravity sag and release effects
- CREEP and DRIFT of material properties
- Distortion due to thin film stress
- High part count of flimsy, high precision components
- Much more difficult computational and metrology challenges

We Live in the Golden Age of Thin Shell X-ray Mirror Technology

Decades of APRA/SAT support have advanced thin-shell mirror technology to the threshold of 1 arc sec

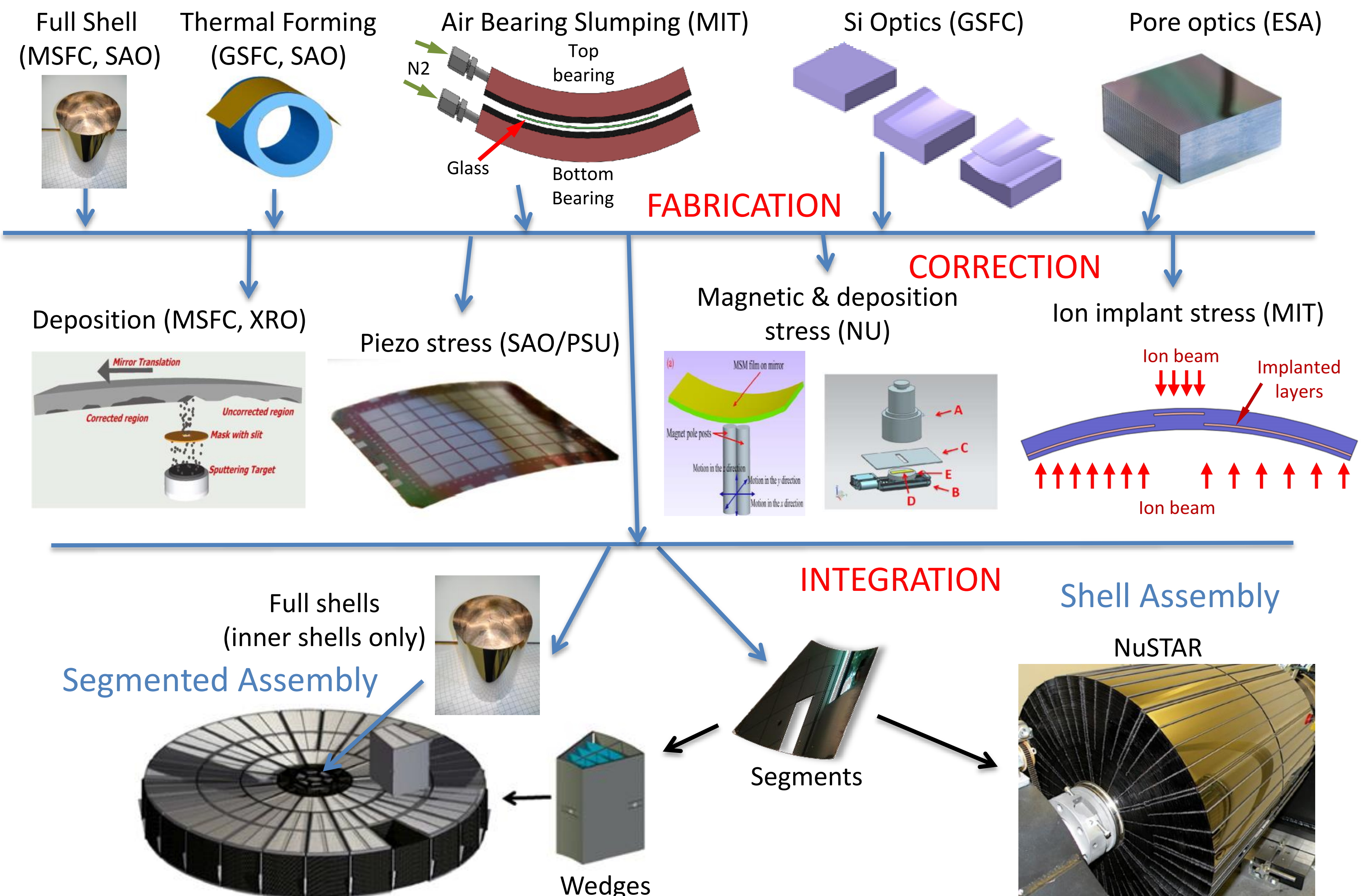
Three strong and highly motivated teams are developing telescope concepts:

- NASA MSFC (Mikhail Gubarev)
  - Full-shell glass and metal mirrors
- NASA GSFC (Will Zhang)
  - Segmented silicon mirrors
- Harvard-SAO (Paul Reid)
  - Piezo-corrected segmented glass mirrors

Rapid progress is being made!

All three teams have announced plans to demonstrate 1.0 arc sec resolution tests with x-rays prior to the Decadal Review

Taxonomy of X-ray Telescope Fabrication



Mirror Fabrication

Full Shell

Metal, fused silica (MSFC, SAO)

Replication

Diamond turn mandrel
Electroform replication

Direct Fabrication

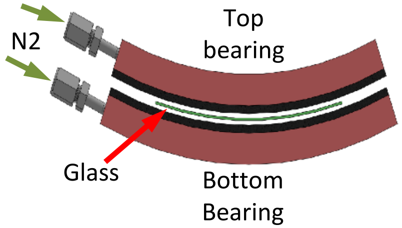
Zeeko polishing machine

Segmented

Glass thermal forming (GSFC, MIT, SAO)

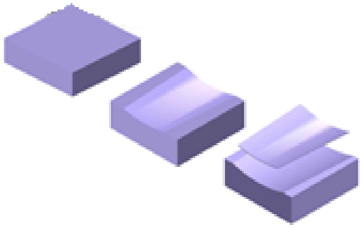
Slumping (GSFC, SAO)

Air bearing slumping (MIT)

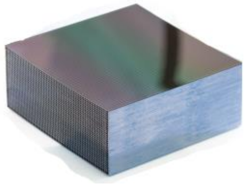


Silicon optics

Slice & polish (GSFC)

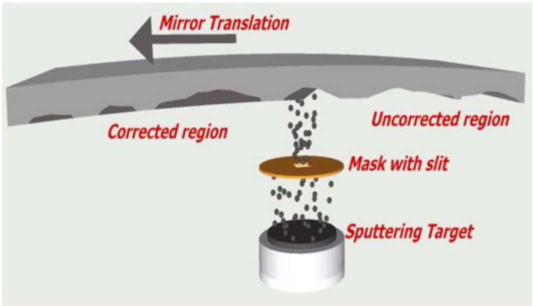


Pore optics (ESA)



Mirror Correction

Material Add or Subtract



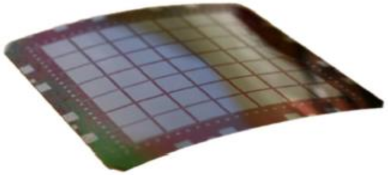
Sputter deposition (MSFC, XRO, Inc.)

Multipass metrology/polish
(GSFC, MSFC)

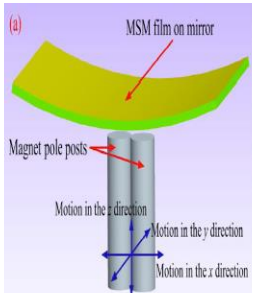
Others (ion polish, magnetorehologic polish, fluid jet polish, etc.)

Stress Layer

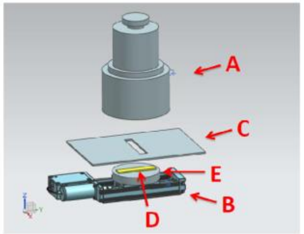
Piezo stress (SAO/PSU)



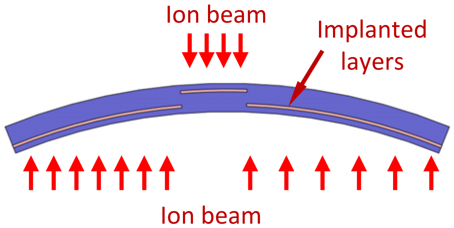
Magnetic stress (NU)



Sputter deposition stress (NU)

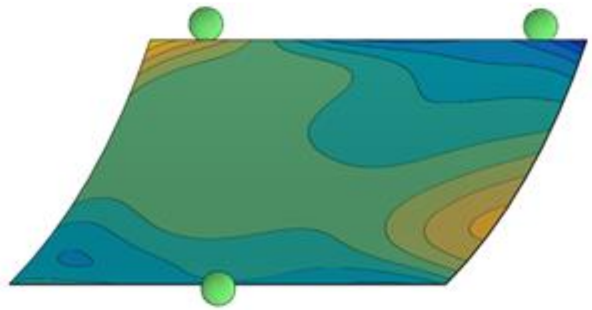


Ion implant stress (MIT)

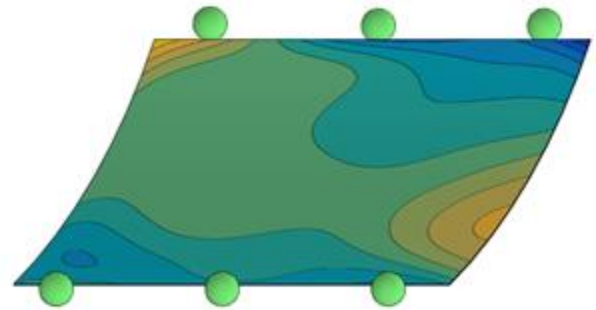


Stress Layer Mirror Correction

A position dependent stress is imparted to “bend out” mirror errors



Kinematically constrained

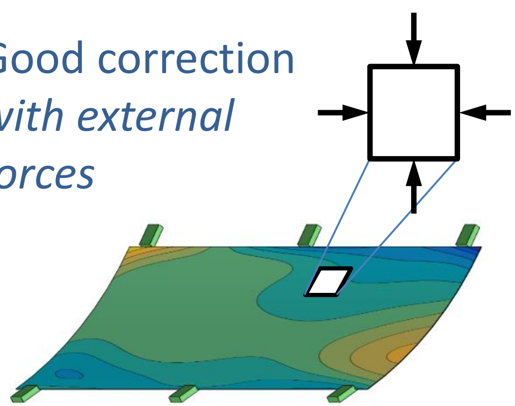


Over constrained

Mirror response to stress layer depends strongly on mirror constraints

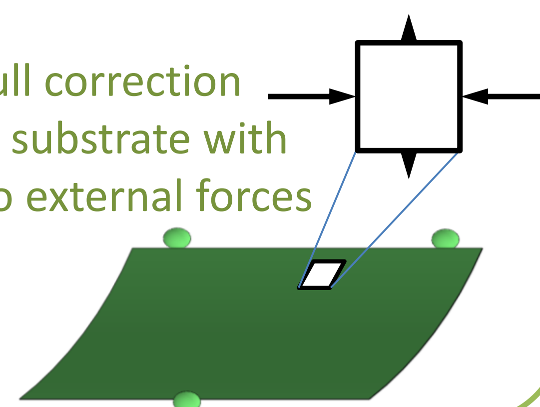
Equi-biaxial stress

Good correction *with external forces*



General plane stress

Full correction in substrate with no external forces



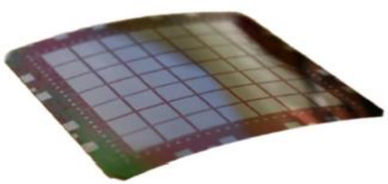
Direction of stress can be critical to obtain good convergence!

Stress Layer Mirror Correction

Technique	Pro	Con
PZT (SAO, PSU)	Electronically addressable	Only compressive stress Only bi-axial stress
Sputtered film (NU)	Compressive and tensile stress	Only bi-axial stress
Magneto restrictive (NU)	General stress	Stress very weak
Ion implant (MIT)	General stress	Requires MeV Ion beam

Dynamic Correction

Piezo stress (SAO/PSU)

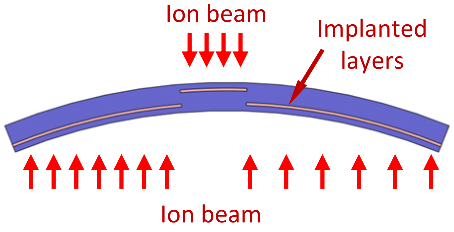


Pro: On-orbit correction forgives many figure and assembly errors

Con: On-orbit reference difficult

Static Correction

Ion implant stress (MIT)



Pro: Simplicity

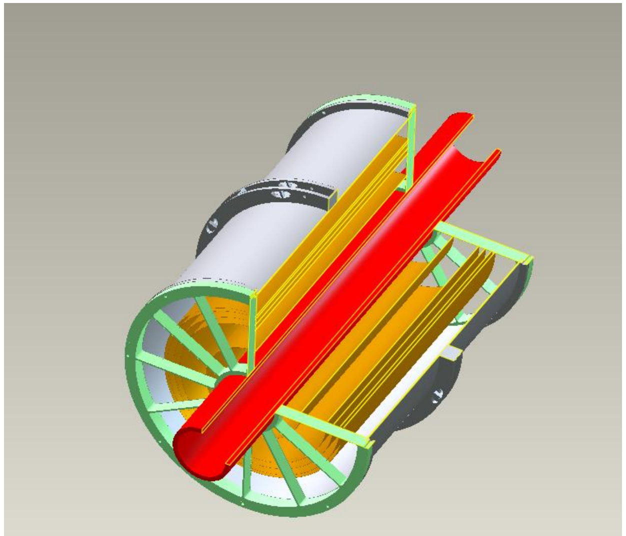
Con: Must prove on-orbit figure will not be compromised

Full-Shell Mirrors

Team led by Mikhail Gubarev, NASA MSFC

Pros:

- Full shell mirrors are stable and can be self-supporting.
- Less obscuration
- Alignment of the H and P segments to each other can be avoided
- Potentially simpler and lower mass support system compared to segmented
- It is possible to use the “one spider” scheme
- Extremely stiff shells resist distortion due to coating stress



A schematic representation of an x-ray telescope module. For simplicity only five mirror shells are shown.

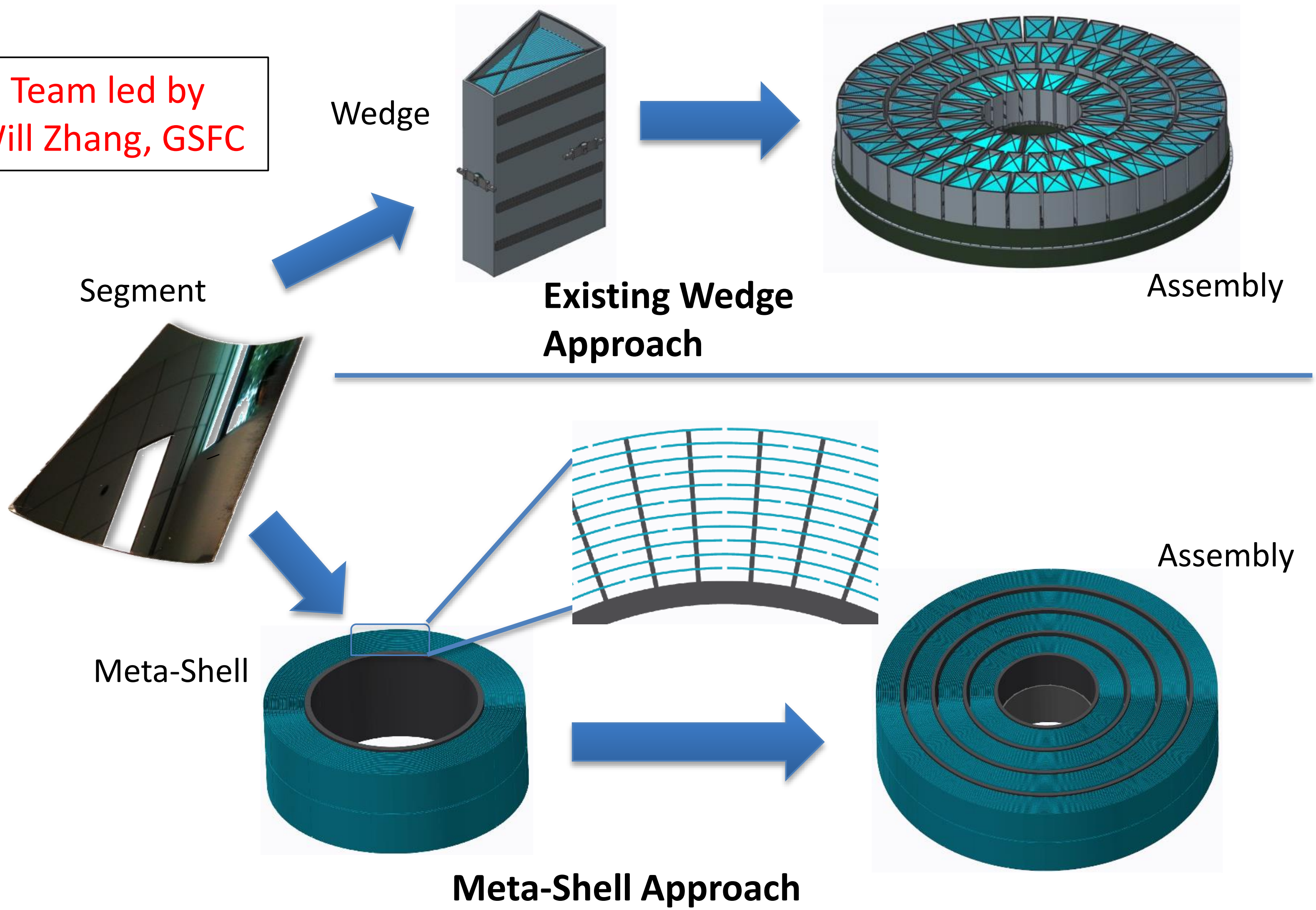
Cons:

- Difficult to scale to large diameters

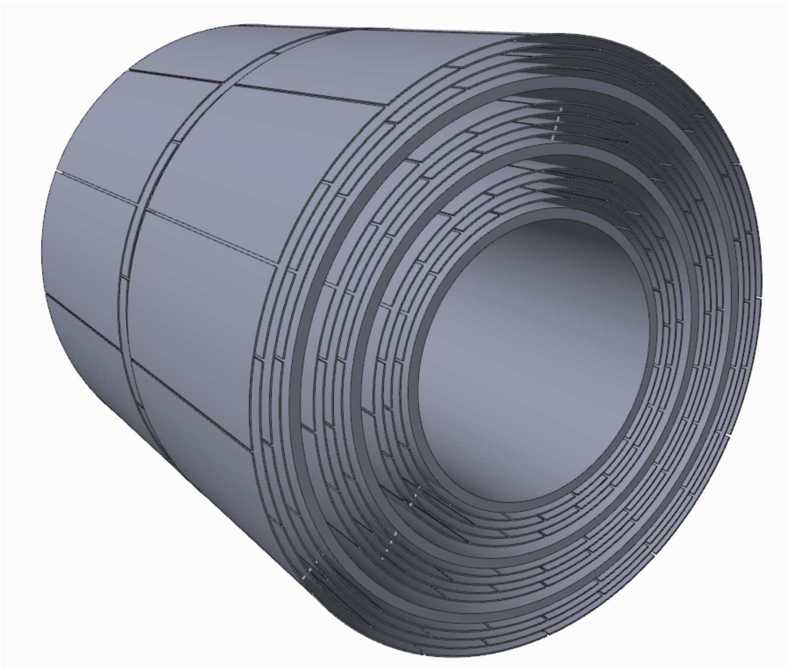
MSFC is targeting the inner XRS mirrors for full shells

Segmented Mirror:
Two Ways to Build an Assembly

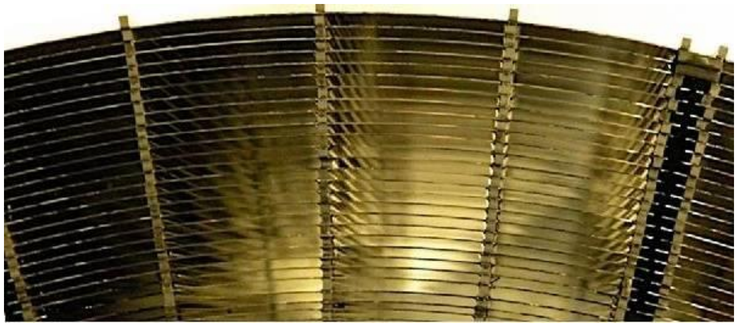
Team led by
Will Zhang, GSFC



“NuSTAR” Assembly Concept



GSFC Assembly Concept (Will Zhang)

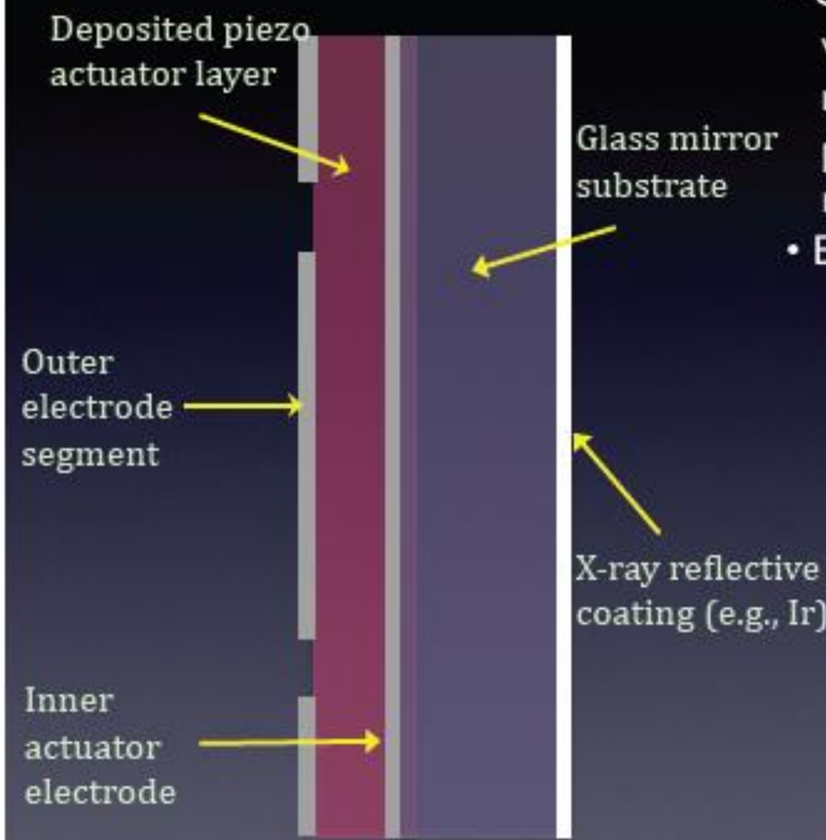


Detail of NuSTAR Mirror

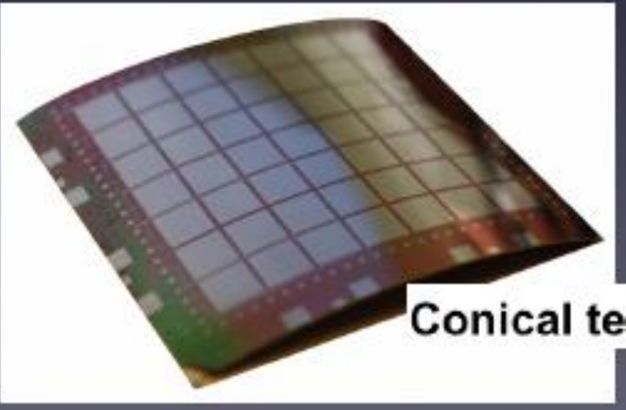
Adjustable X-ray Optics – Quick Intro I

SAO

Schematic X-section



- Continuous thin film (1.5 μm) piezo actuators with independently addressable electrodes on mirror substrate. Low (<10) DC voltage thru piezo thickness produces in-plane stress in piezo, resulting in localized bending of mirror.
- Enables efficient correction of mirror figure for:
  - fabrication errors
  - mounting induced distortions
  - *on-orbit* changes due to thermal environment
    - on-orbit correction enabled by integral strain gauges directly on piezo cells (later).



Conical test mirror

Team led by Paul Reid, Harvard-SAO

Potential Technology Gaps?

- APRA/SAT support has been tremendously important to advance mirror technology
- Are there issues, common too all approaches, that may be poorly served by the APRA/SAT model?

Community mirror metrology assets

Gravity distortion (for example) during mirror metrology is much worse than Chandra.

Do we have in hand the x-ray metrology assets necessary to demonstrate a sub-1” mirror?

Community computer modelling assets

High fidelity computer modelling of mirrors in a flight environment (thermal gradients, creep and drift, vibration, etc.) is going to be ***absolutely essential!***

Do we have in hand the computational assets necessary to demonstrate sub-1” flight mirror performance?

Telescope Model-Ability

- Segmented x-ray telescopes require a large number of mirrors
- Depending on mounting scheme, many parts and joints per mirror are required
- Modeling complexity increases significantly as piece part size decreases and number of optics increases
- Significant modelling effort will be required to capture all critical issues which can effect telescope PSF and survivability:
  - Thermal distortion, gravity release, creep, material stress, etc.
- Telescope designs with poor model-ability may be demerited by Decadal

Estimated model degrees-of-freedom (DoF) for segmented mirror (source: Lester Cohen, SAO)

Mission	Mirrors	Model DoF (in millions)
Chandra	8	~7
JWST	18	~70
XRS	>10,000	~700

Mirror Thin Film Stress

Film stress is a significant issue for thin-shell mirrors

Inner-diameter **full shell mirrors** nearly immune to coating stress

Segmented mirrors easily distort with film stress

Static Segmented

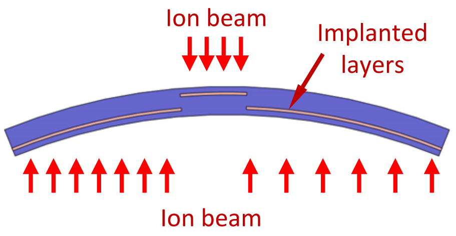
- Coating stress distorts mirrors
- Sputtering and ALD approaches so far have not solved the problem

Dynamic Segmented

- PZT film stack imposes severe distortion on mirror (>10 microns)
- So far the addition of stress balanced layers has not solved the problem

More work is needed!

Ion implant technique has been shown to reduce film stress

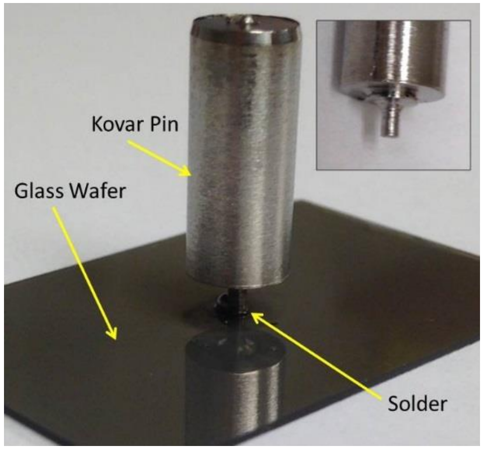


Epoxy Creep

Epoxy is a terrible material for bonding optics
- High creep, high CTE, low strength, hydroscopic

It's only advantage is that it is better than alternatives!

MIT is developing (with APRA support) a laser-assist mirror bonding technique which could eliminate epoxy



Kovar pin soldered to D263 glass

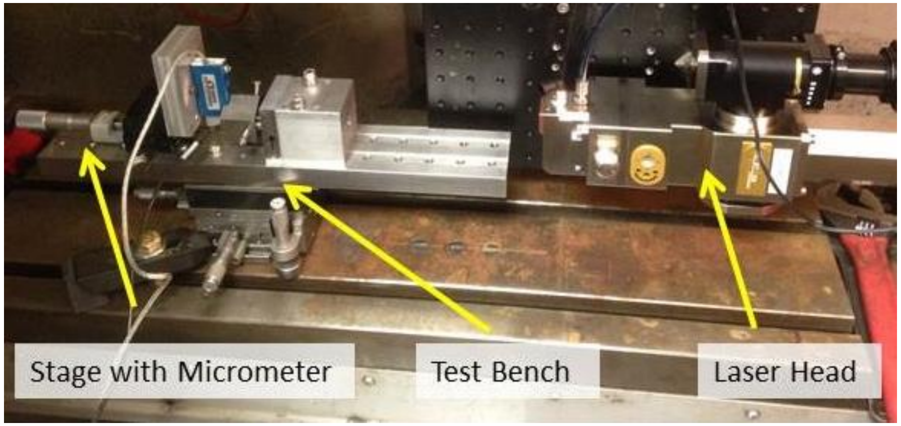


Photo of apparatus in laser test chamber at IPG Photonics Inc.

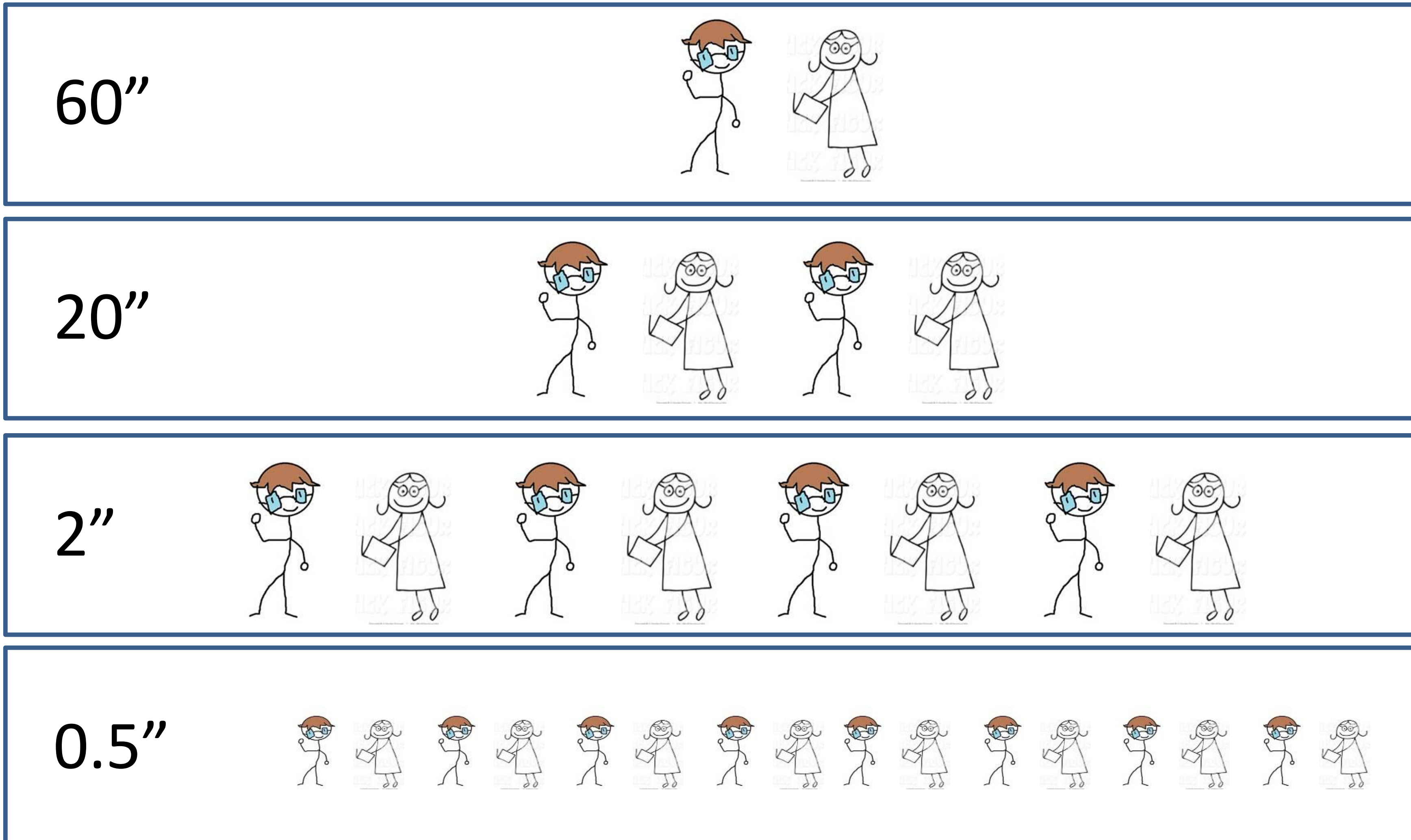
APRA/SAT-Supported Mirror Development

Estimate 40-50 people (~$5M/year)

- NASA MSFC
- NASA GSFC
- Harvard-SAO
- MIT
- Penn State
- Northwest
- Alabama

This is a small and fragile community.

R&D Manpower Levels Increase with Resolution



Will funding be there to support this ecosystem as resolution improves?

Summary

- The US x-ray telescope engineering and science community is energized by the challenge of the XRS mission concept
- Chandra experience and decades of NASA support for thin shell mirrors is starting to pay off
- Three very competitive concepts are being developed
- A high degree of community enthusiasm and confidence that a ~1 arc sec mirror x-ray test can be demonstrated to the Decadal
- Keen interest in enhanced community cooperation and communication, pulling together towards a common goal
- Strong desire to set common goals, establish objective criteria for success, and build tools to solve common problems
- Intense desire to put forward the best possible science and technology package before the Decadal to ensure XRS success

The X-ray Surveyor

Let’s do this!