Lynx Mirror Assembly: Seeing Through the Details

Jessica A. Gaskin (Lynx Study Scientist, NASA MSFC)

PCOS/Aerospace TRL Assessment
May 2017

<table>
<thead>
<tr>
<th>STDT</th>
<th>Total Gaps</th>
<th>TRL 2 Gaps</th>
<th>TRL 3 Gaps</th>
<th>TRL 4+ Gaps</th>
</tr>
</thead>
<tbody>
<tr>
<td>HabEx</td>
<td>13</td>
<td>0</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>LUVOIR</td>
<td>10</td>
<td>1</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>Lynx</td>
<td>5</td>
<td>X</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>OST</td>
<td>11</td>
<td>3</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>
Challenges

Science Driven Requirements

<table>
<thead>
<tr>
<th>Lynx Optical Assembly</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Angular resolution (on-axis)</td>
<td>0.5 arcsec HPD (or better)</td>
</tr>
<tr>
<td>Effective area @ 1 keV</td>
<td>2 m² (met with 3-m OD)</td>
</tr>
<tr>
<td>Off-axis PSF (grasp), A*(FOV for HPD &lt; 1 arcsec)</td>
<td>600 m² arcmin²</td>
</tr>
</tbody>
</table>

Chandra did it! Why can’t Lynx?

- Large effective area is achieved by nesting a few hundred to many thousands of co-aligned, co-axial mirror pairs.
- Must fabricate thinner mirrors to allow for greater nesting of mirror pairs and larger effective area while reducing mass.
- These thin mirrors must be better than 0.5” HPD requirement.
- Must mount and coat these thin optics without deforming the thin optic, or must be able to correct deformations.
Challenges

• Systems engineering
  • Error budgets
  • Defining local and global structures and allocating requirements to each
• Understanding and mitigating coating stresses
• Structures and mounting
  • Epoxy creep
  • Alternative pinning techniques
  • Different challenges for sub-assemblies and aggregation
• Thermal control of the assembled telescope
• Community mirror metrology (and calibration) assets
  • Gravity distortion (for example) during mirror metrology is much worse than Chandra

M. Pivovaroff (SPIE 2016)

Example Working Error Budget

L. Cohen (OWG Talk 2016)
Overcoming Challenges

3 Viable Lynx Mirror Architectures Studied

- Full Shell (K. Kilaru/USRA/MSFC, G. Pareschi/OAB)
- Adjustable Optics (P. Reid/SAO)
- Meta-Shell Si Optics (W. Zhang/GSFC)

One of these will be selected for the Design Reference Mission Concept. Additional feasible concepts will be included in the Final Report to the Decadal.

Must Develop Technology Maturation Plan:

- Define State-of-the-art
- Maturation (and development) Milestones
- Schedule & Cost
Lynx Mirror Assembly

**FABRICATION**
- Thermal Forming (GSFC, SAO)
- Full Shell (Brera, MSFC, SAO)
- Si Optics (GSFC)
- Air Bearing Slumping (MIT)

**CORRECTION**
- Piezo stress (SAO/PSU)
- Deposition (MSFC, XRO)
- Magnetic & deposition stress (NU)
- Ion implant stress (MIT)
- Ion beam figuring (OAB)

**INTEGRATION**
- Full shells Assembly
- Segmented Wedge Assembly
- Meta-Shell Assembly

Schattenburg talk to NASA PCOS SIG, 04/2016 - Modified
Full Shell Status (G. Pareschi & Team - OAB)

Same approach used for Chandra, but mirrors (shells) need to be thinner
- Limited (<200) number of shells (produced/assembled)
- Azimuthal symmetry of the shells (measure/correct)
- Coating effects are mitigated by the symmetry
- Primary and secondary surface can be joined or detached

Some issues to be investigated
- Large shells need to be thicker: thickness drives the mass of the assembly
- Large shells are not easy to sustain during manufacturing
- The surface correction and coating process may be more difficult

Fine grinding to correct the out of roundness and longitudinal profiles

After the grinding, the use of spinning bonnet tool has been successfully implemented on the precision lathe to obtain the profile

Integration into the Shell Supporting System
The superpolishing made more effective using 3M Trizact abrasive tapes

**Trade-off study on mounting configuration successfully completed**

Superpolishing time much improved: mean PTV and RMS (MFT 10x) In blue are reported the data of the last tests on shells#4 compared to the typical time needed for simple pitch tool (in black).

- Continue to optimize the configuration
- The entire polishing process (including the ion-figuring correction) is being tested on dummy shells
- Waiting for (expected!) funds from ASI for the development of a representative breadboard based on 2 shells to be X-ray tested based on the mounting configuration
Correcting slumping errors
Control mirror figure to ~ 0.5 arcsec HPD

• Mounted adjustable mirror 0.4 mm thick, 112 piezo cells
• ACF bonded electrical connections

Relative Correction
Left – slumped mirror figure = figure to be corrected (~ 7 arcsec HPD @ 1keV, 1 surface); Right – measured (using metrology) difference between imparted figure correction and desired figure correction (~ 0.5 arcsec HPD)

Critical proof-of-concept aspect met for adjustable X-ray mirrors. Still lots to do before 0.5” HPD optics can be realized.
Adjustable Optics Status

- Slumping to high precision Wolter-I mandrel
- Implement side mirror mount
  - Modeled and designed, parts being ordered
- Incorporation of next level of back surface electronics integration
  - Insulating layer with conductive vias and narrower gap between piezo cells
    - 0.2mm vs 1.0mm
    - Mirrors in fabrication now, ~ 288 piezo cells (5mm x 5mm)
- Repeat optical mounted mirror test describe on previous slide with higher fidelity mirror
- Single mirror X-ray test
- Extend single mirror mount to mirror pair
- Incorporate row-column addressing via ZnO thin film transistors printed directly on mirror
- Mount, correct, align, and test mirror pair at MSFC SLF with target 1 arcsec HPD 1 keV performance.
1. **40,000 Mirrors**

2. **12 Meta-shells**

3. **1 Assembly**

**Four Technical Elements**

1. Precision-polishing of Mono-crystalline silicon.
2. Coating to maximize reflectivity w/o distortion.
3. Alignment using four precision-machined spacers.
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.
The meta-shell optics have been shown by STOP (structural, thermal, and optical performance) analysis to meet:

- Mass, effective area, FOV, and stray-light requirements,
- Structural requirements to survive launch, and
- Thermal and gravity release requirements to preserve PSF on-orbit.

The four technical elements have been validated by building and X-ray-testing mirror modules, achieving 2.2" HPD as of Dec 2017.

Further refinement for all four elements is needed to meet PSF requirements.

**Status and Expectations**

- **Silicon Meta-Shell Optics Status**

  - **Secondary Mirror**
  - **Primary Mirror**
  - **Silicon Plate**

  **2.2" HPD image, Full illumination with Ti-K X-rays (4.5 keV)**
• 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
LMAT Process:

- Kickoff Telecon with Steering Group
- Kickoff Telecon with the LMAT Working Group
- Establish consensus criteria for a successful trade outcome
- Description of options for evaluation
- Evaluation of Science, Technical, and Programmatic criteria
- Reach consensus by LMAT Consensus Members on evaluation criteria, risks, and opportunities
- Reach consensus via Consensus Member recommendation
- LMAT delivery recommendation to the STDT by 7/13/18

- Using JPL-facilitated Kepner-Tregoe process (*JPL contributed effort*)
- Each optics technology will be evaluated against the decision criteria by programmatic, technical and science teams
- Trade criteria is chosen by the full LMAT team and requires consensus from the ‘Consensus Members’
**Facilitator**

<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gary Blackwood</td>
<td>NASA ExEP/JPL</td>
</tr>
</tbody>
</table>

**Consensus Members**

<table>
<thead>
<tr>
<th>Members at Large</th>
<th>Affiliation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mark Schattenburg</td>
<td>MIT</td>
</tr>
</tbody>
</table>

**Advocates**

<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kiran Kilaru</td>
<td>USRA/MSFC Full Shell</td>
</tr>
<tr>
<td>Giovanni Pareschi</td>
<td>INAF/OAB</td>
</tr>
<tr>
<td>William Zhang</td>
<td>NASA GSFC Silicon Meta-shell</td>
</tr>
<tr>
<td>Peter Solly</td>
<td>NASA GSFC Silicon Meta-shell</td>
</tr>
<tr>
<td>Paul Reid</td>
<td>Harvard SAO Adjustable Segmented</td>
</tr>
<tr>
<td>Eric Schwartz</td>
<td>Harvard SAO Adjustable Segmented</td>
</tr>
</tbody>
</table>

**Science Evaluation Team (SET)**

<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daniel Stern</td>
<td>NASA JPL</td>
</tr>
<tr>
<td>Frits Paerels</td>
<td>Columbia University</td>
</tr>
<tr>
<td>Ryan Hickox</td>
<td>Dartmouth</td>
</tr>
</tbody>
</table>

**Technical Evaluation Team (TET)**

<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gabe Karpati</td>
<td>NASA GSFC TET Lead</td>
</tr>
<tr>
<td>Ryan McClelland</td>
<td>NASA GSFC structural/thermal</td>
</tr>
<tr>
<td>Lester Cohen</td>
<td>Harvard SAO structural</td>
</tr>
<tr>
<td>Gary Mathews</td>
<td>Kodak systems engineering</td>
</tr>
<tr>
<td>Mark Freeman</td>
<td>Harvard SAO thermal/SE</td>
</tr>
<tr>
<td>David Broadway</td>
<td>NASA MSFC coatings</td>
</tr>
<tr>
<td>Dave Windt</td>
<td>Company coatings</td>
</tr>
<tr>
<td>Marta Civitani</td>
<td>OAB optical design, test</td>
</tr>
<tr>
<td>Paul Glenn</td>
<td>Company metrology</td>
</tr>
<tr>
<td>Ted Mooney</td>
<td>Harris polishing</td>
</tr>
<tr>
<td>Chip Barnes</td>
<td>Ball systems engineering</td>
</tr>
</tbody>
</table>

**Programmatic Evaluation Team (PET)**

<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jaya Bajpayee</td>
<td>NASA ARC PET Lead</td>
</tr>
<tr>
<td>John Nousek</td>
<td>Penn State</td>
</tr>
<tr>
<td>Karen Gelmis</td>
<td>NASA MSFC</td>
</tr>
<tr>
<td>Steve Jordan</td>
<td>Ball</td>
</tr>
<tr>
<td>Charlie Atkinson</td>
<td>NGAS</td>
</tr>
</tbody>
</table>

**Subject Matter Experts, Observers and Guests (not inclusive):**

<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denise Podolski</td>
<td>NASA STMD</td>
</tr>
<tr>
<td>Rita Sambruna/Dan Evans</td>
<td>NASA HQ</td>
</tr>
<tr>
<td>Terri Brandt/Bernard Kelly</td>
<td>NASA PCOS</td>
</tr>
<tr>
<td>Vadim Burwitz</td>
<td>MPE</td>
</tr>
<tr>
<td>Susan Trolier-McKinstry</td>
<td>Penn State</td>
</tr>
<tr>
<td>Casey DeRoo</td>
<td>U. Iowa</td>
</tr>
<tr>
<td>Kurt Ponsor</td>
<td>Mindrum</td>
</tr>
<tr>
<td>TBD</td>
<td>Optics Working Group</td>
</tr>
<tr>
<td>TBD</td>
<td>Optics Working Group</td>
</tr>
</tbody>
</table>

**Steering Group**

<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feryal Ozel</td>
<td>University of Arizona</td>
</tr>
<tr>
<td>Alexey Vikhlinin</td>
<td>Harvard SAO</td>
</tr>
<tr>
<td>Jessica Gaskin</td>
<td>NASA MSFC</td>
</tr>
<tr>
<td>Robert Petre</td>
<td>NASA GSFC</td>
</tr>
<tr>
<td>Doug Swartz</td>
<td>NASA MSFC</td>
</tr>
<tr>
<td>Jon Arenberg (Bill Purcell/Lynn Allen)</td>
<td>NGAS (Ball/Harris)</td>
</tr>
<tr>
<td>Jaya Bajpayee</td>
<td>NASA ARC consensus member</td>
</tr>
<tr>
<td>Gabe Karpati</td>
<td>NASA GSFC consensus member</td>
</tr>
<tr>
<td>Mark Schattenburg</td>
<td>MIT consensus member</td>
</tr>
</tbody>
</table>
AGENDA

• Day 1: Develop consensus on trade criteria

• Day 2:
  • Reach consensus on trade criteria;
  • Introduction of mirror architecture option that will be evaluated in the trade
  • Slides should address:
    • Description of flight architecture
    • Current state of the technology (recent manufacturing, test and/or analysis results)
    • Plans between now and early 2020 (prior to Decadal)
    • Anything else the advocate considers important for LMAT to know

Face-to-Face Trade Criteria Meeting

• Date: March 21 (1pm-5pm – or later as needed) – 22 (8am-2pm)

• Location: Hilton Chicago O'Hare Airport, 10000 W O'Hare Ave, Chicago, IL 60666

• Dublin/London Room
Thank You!
https://www.astro.msfc.nasa.gov/lynx/
Mechanical Design

- Internal contamination door & gratings mechanisms
- Chandra Heritage Considered
- X-ray Microcalorimeter Designs
- Thrust tube design:
- Internal strut design:
- ~100 cm OD
- X-rays in from telescope
- Filter wheel
- X-ray calibration source electronics (high voltage)
- Compressor on separate tower (vibration isolation)
- Deck: to be attached to movable table and focusing mechanisms
- Bipod cryostat supports
- Focal Plane Assembly
- Calibration sources
- 70 cm OD

S. Bandler, NASA GSFC

Integrated Science Instrument Module

- X-ray Microcalorimeter
- Optical Assembly
- Outer Door/Sunshade
- Mono-prop tanks
- Grating Array
- Magnetic Broom
- Filter wheel
- 50 cm OD
- 100 cm OD

S. Bandler, NASA GSFC