Lynx Mission Costing Methodology
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Introduction

- Strong foundation for Lynx mission costing effort:
  - Clear science, mission and Observatory architecture requirements for a closed DRM design
  - Availability and leverage of deep Chandra heritage for spacecraft design, mission architecture and operations to minimize costing unknowns
  - Detailed inputs from Lynx technical and programmatic experts
  - Availability of Chandra program and contracting personnel for insights and lessons learned on programmatic, technical and costing analysis
  - Rapidly maturing Lynx technologies with clear development paths to achieve necessary TRL milestones

- Costs validated at element and mission level via analogies, in-family comparisons and multiple, independently conducted cost estimates with different approaches

- Lynx mission cost range across all methodologies is $4.8B at 40% confidence level (CL) to $6.2B at 70%CL in $FY20
  - Cost confidence results highly consistent at ~40% CL, reflecting well-developed mission design with high heritage and lessons learned from past and present missions
  - Cost results diverge at 70% CL, reflecting appropriate pre-formulation-stage uncertainties

- Full details of entirety of costing efforts included in non-public Lynx Cost Book
Costing Inputs: Schedule Pre-Phase A through TRL6

- Instrument and Optics Technology Development Roadmaps lay out detailed pre-Phase A / Phase A schedules and milestones for achieving requisite TRL levels

- Requirements / assumptions:
  - Pre-Phase A funding start 10/2021
  - Architecture selection 2/2024
  - Phase A start 10/2024 / technologies at TRL5
  - Mission PDR 2/2028 / technologies at TRL6
  - All Lynx technologies remain actively funded during Pre-Phase A
    - Multiple decision points during pre-Phase A for technology down-select
    - Final down-select prior to start of Phase A based on ability to meet Lynx requirements
    - WFIRST technology development funding levels provided sanity check

- Included schedule margins for achieving TRL milestones based on risk assessments

- Iterated to arrive at schedule consistent with assumptions, technology development plans, and the overall project lifecycle schedule

- Pre-Phase A / Phase A technology development schedule provided in Figure 7.1 of Lynx Concept Study Report
Costing Inputs: Schedule Phase A - E

- Reflects inputs and development planning from Lynx technology, engineering and science operations teams

- Is consistent with technology development and current DDT&E plans for the DRM optics and instruments

- Leverages heritage and analogous AI&T, on-ground calibration, and mission and ground operations activities

- Is aligned with NASA project lifecycle milestones, and GAO best practices consistent with pre-Phase A project maturity

- Full Lynx lifecycle schedule provided in Figure 8.3 of Lynx Concept Study Report
Costing Inputs: Schedule Phase A - E

- Compared phase durations with WFIRST and Chandra as sanity check
- Included total schedule margin of 19 months consistent with MSFC practices, project complexities and risks
- Critical path runs through LXM DDT&E, through ISIM I&T, and through XRT, Observatory and launch vehicle I&T activities
- Further optimization possible based on mirror manufacturing studies, AI&T sequencing and on-ground calibration scope
- LCIT Comment: “…schedule well done”

<table>
<thead>
<tr>
<th>Project Milestone</th>
<th>~Milestone Date</th>
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<tbody>
<tr>
<td>Tech. Dev. / Start of Pre-Phase A</td>
<td>10/2021</td>
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<tr>
<td>Architecture Decision</td>
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<td>LRD</td>
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<tr>
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<tr>
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While notional, project lifecycle schedule provides a credible path to launch in the mid-2030’s
Costing Inputs: WBS, MEL and Power Schedule

• Work Breakdown Structure (WBS)
  – Provides project organizational structure consistent with NASA guidance
  – Similar to Chandra for organizational and analogous cost comparisons
  – Defined to Level 3 for all elements, and Level 6 for XRT and SCE consistent with Observatory design details
  – Summary WBS provided in Table 8.4 of Lynx Concept Study Report (full WBS provided in Appendix E)

• Master Equipment List (MEL)
  – Provides predicted mass for XRT and SCE systems, using sub-system and component-level basic mass
  – Predicted mass based on industry-standard MGA for Pre-Phase A maturity and TRL considerations
  – Full MEL provided in Appendix D of Lynx Concept Study Report

• Power Schedule
  – Provides SCE, optics and instrument design power levels with margin for all operational phases
  – Power system components designed and costed per power schedule
  – Power schedule provided in Table 6.16 of Lynx Concept Study Report

• LCIT Comment: “…WBS complete & MEL and PEL reflect a lot of work traceable to design”
Costing Methodology Overview

• Pre-Phase A cost estimates provided by technologists in the Technology Development Roadmaps

• Phase A – E
  – Enabled by relatively straightforward and detailed Lynx Observatory design, detailed technology maturation plans, and use of rich Chandra heritage and lessons learned
  – Lynx lifecycle cost estimated and validated using multiple methods:
    • Parametric Cost Estimate:
      – Primary project estimate (point estimate + confidence level (CL) analysis)
      – Includes multiple parametric models for all cost elements
      – Consistent with pre-Phase A project maturity, GAO Best Practices and NASA Cost Estimating Handbook
    • Validation Methods:
      – Comparison to escalated (FY20) Chandra actuals (point estimate)
      – Grassroots estimate (point estimate)
      – Non-advocate Independent Cost Estimate (ICE) (point estimate + CL analysis)
      – Independent Cost and Technical Evaluation (CATE) (point estimate + CL analysis)
  – Validation estimates yielded results in reasonable agreement with parametric
Parametric Estimate

- Parametric model is primary cost estimate for Lynx
  - Consistent with pre-formulation stage design
  - True bottoms-up with vendor quotes not feasible
- Utilized multiple industry-standard models in parametric cost analysis
- Used subject matter expert inputs at the component level for all elements
- Incorporates high Chandra architecture heritage, high-TRL spacecraft components, and detailed designs for the DRM technologies

<table>
<thead>
<tr>
<th>General GR&amp;A for Lynx Parametric Estimate</th>
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<tbody>
<tr>
<td><strong>Parameter</strong></td>
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<tr>
<td>Baseline Cost</td>
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<tr>
<td>Spares</td>
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<tr>
<td>Phase A Estimate</td>
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<td>Public Outreach Estimate</td>
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Parametric Estimate

- Other inputs and assumptions:
  - Per NASA HQ direction, Launch vehicle cost (for 2030’s heavy lift vehicle) was a pass-through
  - LXM cost was a pass through from GSFC Instrument Design Lab (IDL) cost analysis
  - Funded schedule reserves included for identified schedule risks and critical path margins

- Cost model input tailoring:
  - Necessary given scarcity of X-ray mission analogies in the historical databases from which the CERs are drawn
  - Able to realistically represent Lynx technologies given relatively high TRL and detailed, current knowledge of development approach
  - Specific parametric model inputs provided in Table 8.7 in Lynx Concept Study Report

The DRM parametric mission cost is in the range of $4.8B at a 40% CL to $6.0B at a 70% CL in FY$20
Parametric Estimate
Lynx X-ray Mirror Assembly

• LMA parametric costing given special consideration due to lack of directly applicable historical comparisons
• Complex but cost-effective assembly due to many similarly manufactured and assembled sub-components
• Modeled assuming “learning curve” to account for repeated manufacturing processes
  – “make”->”major modification”->”average modification”
• Other model specifics targeted realistic development and manufacturing
  – “Staggered development start” of meta-shells to benefit from development of first one
  – “Concurrent production” to take advantage of assumed 12 production lines
• Estimate includes cost for LMA prototype (3 meta-shells, 9 fully populated modules, mass dummies for all else), consistent with TRL maturation plans
• GSFC Silicon Meta-shell optics team provided design details to support veracity of cost modeling inputs and assumptions
• LMA manufacturing risk accounted for in 9 months of costed schedule margin

Parametric LMA estimate within 4% of GSFC Silicon Meta-shell Optics team grassroots estimate
Spacecraft parametric costing also given special consideration due to high levels of heritage in subsystem design.

“Heritage Rating” settings in parametric model reflect degree of modifications assumed for each subsystem, and play a role in the cost.

Overall Heritage Rating of 5.1 for Lynx Spacecraft system is between “major” and “minor” modification, consistent with the design.

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Subsystem Heritage Rating</th>
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<tbody>
<tr>
<td>Structure</td>
<td>5.0</td>
</tr>
<tr>
<td>Thermal Control</td>
<td>3.8</td>
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<tr>
<td>Electrical Power &amp; Distribution</td>
<td>4.2</td>
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<tr>
<td>Attitude Determination &amp; Control</td>
<td>6.2</td>
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<tr>
<td>Reaction Control</td>
<td>4.2</td>
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<tr>
<td>RF / Communication</td>
<td>6.8</td>
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<tr>
<td>Command &amp; Data</td>
<td>5.8</td>
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<td>Cost Model Flight System Heritage Rating</td>
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Heritage Rating Key:
- >0 = All items @ TRL< 7
- 1 = New, but standard practice
- 3 = Major Modification
- 7 = Minor Modification
- 10 = Exact Repeat (copy)

No new developments for spacecraft; only modifications to existing components.
Chandra Analogy

- Mission architecture heritage and availability of actual costs make comparison of the Lynx parametric estimate to escalated ($FY20) Chandra costs possible.

- A side by side comparison of requirements and costs shows that many Lynx elements are analogous or comparable to Chandra:
  - Spacecraft elements and operations very similar, HDXI ~ACIS, XGS ~HETG+ACIS
  - Summary of comparisons provided in Table 8.9 of Lynx Concept Study Report

- Lynx elements less amenable to direct comparison to Chandra are the LMA and LXM:
  - LMA:
    - Base material (monocrystalline Si) is inexpensive and readily available
    - Laboratory performance of machinery to shape, polish and smooth mirror segments has been demonstrated
    - Flight production is modular with assembly line cost efficiencies
  - LXM design leverages successes from Hitomi, XRISM and Athena
  - Costs for these elements are well understood

Huge gains in capability that Lynx provides do not directly translate into huge cost increases over inflated Chandra actuals.
Grassroots Estimate

- Skilled and diverse team of experts developed a grassroots estimate for each WBS Level 2 code, and WBS Level 3 code in some cases
  - Team included Chandra project and prime contractor team members, and Lynx science, engineering and technology team members
- Estimates included a mix of Chandra-analogous estimates, scaled actuals for Chandra prime contractor activities, and true grassroots based on Lynx development planning
- Launch vehicle cost same as NASA HQ provided pass-through used for parametric
- Fee and 30% reserves applied as applicable
- Detailed BOE provided in Table 8.11 of Lynx concept Study Report

Lynx parametric estimate is within 4% of grassroots estimate
Additional Validation Assessments

Non-Advocate Independent Cost Estimate (ICE)

- The MSFC Engineering Cost Office performed a non-advocate ICE and uncertainty analysis on the Lynx parametric estimate.
- ICE addresses uncertainty in estimating methods, input parameters, and design complexity, using Cost Office assumptions and processes.
- Produced uncertainty curve for project cost.
- Lynx parametric estimate (with reserves) at 38% CL on ICE uncertainty curve.
- Per MSFC Cost Office analysis, 38% CL substantially better than typical level of 15% for NASA missions at this stage.

Independent Cost & Technical Evaluation (CATE)

- Lynx team procured services to perform an independent CATE for further costing validation.
- Contractor developed risk-based project cost estimate and schedule forecast:
  - Developed detailed, independent parametric cost estimate.
  - Analyzed project schedule, Technology Development Roadmaps & DRM architecture to determine missing or underestimated development costs and schedule risks.
  - Produced uncertainty curves for total project cost and schedule.
- 40% CL on CATE uncertainty curve within 1% of Lynx parametric.

Independent risk assessment results, "...consistent with historical NASA mission cost growth behavior”

Lynx parametric cost estimate is, “...reasonable, credible, reproducible, and consistent with the DRM parameters”
Lynx Costing Effort Summary

**Drum**

**Chandra Actuals**
- Analogous and comparable costs across most elements
- Mirror, LXM, SCE and operations costs understood

**Grassroots Estimate**
- Expert team
- *Chandra* heritage
- *Chandra* labor actuals for similar effort

**Non-Advocate ICE**
- Uncertainty analysis on parametric models
- Reserves added to achieve confidence levels

**Independent CATE**
- ICE and uncertainty analysis
- Technology, schedule and risks incorporated in cost

**Credibly-costed Mission**
- Cost validation analysis results range from -11% to +28% of parametric estimate
- Parametric estimate consistent with 40% confidence level on CATE and Non-Advocate cost curves

**LCIT Comment:** “…cost estimate very well done and credible…with understanding of task at hand”
Lynx Mission Costing
Closing Comments

- Lynx mission benefits greatly from Chandra heritage and lessons learned, straightforward Observatory design, rapidly maturing technologies with clear maturation paths, and a relatively low risk posture

- All DRM technologies are actively funded, and will continue development per detailed roadmap plans, with risk and progress-based decision points up through the final architecture selection

- Lifecycle schedule is consistent with DRM technology development plans, includes analogous and heritage mission lessons learned, and includes conservative margins consistent with development risks

- Mission parametric costing effort takes advantage of multiple models and analogous elements for comparison, and detailed design knowledge to tailor inputs as necessary for credible results

- Costing effort goes beyond parametric analysis to include multiple, separately-conducted cost validation exercises providing additional peer reviews, sensitivity analyses and independent crosschecks
  - Close clustering of the costing results around the parametric
  - Good agreement, especially for this phase of mission

Substantial effort by entire Lynx team resulted in thorough and credible costing for a pre-formulation stage mission