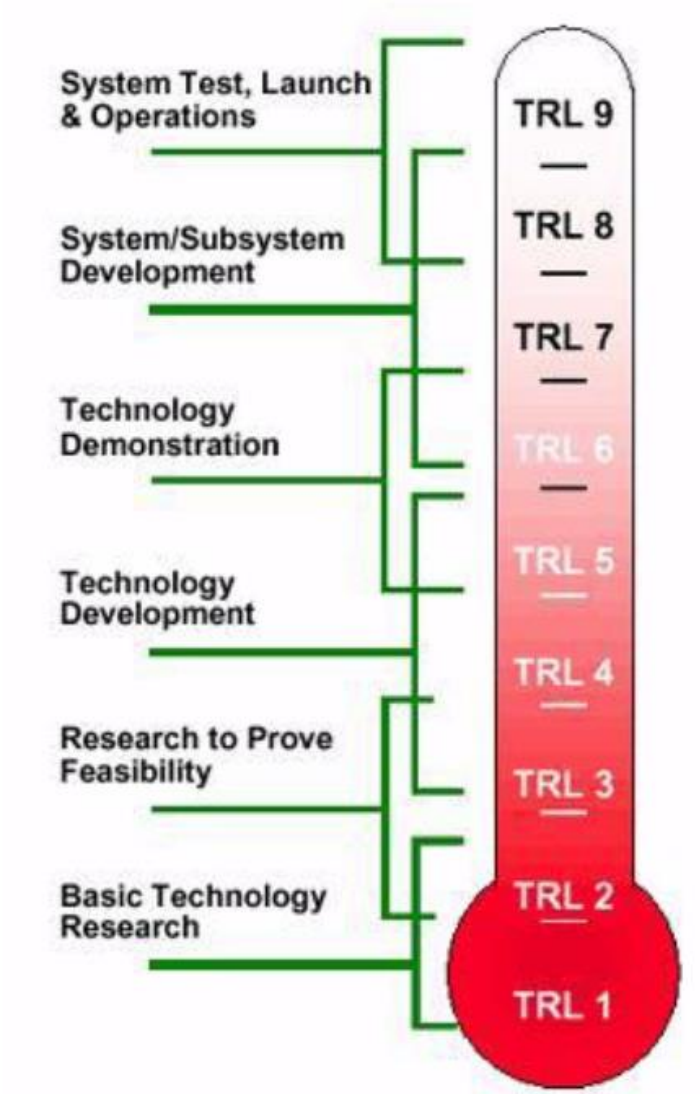
Concept Maturity Level

-What is this?

-Why is it important?

We Need a Language or a Yardstick – Just Like TRL… It Has Become a Powerful Communications Tool



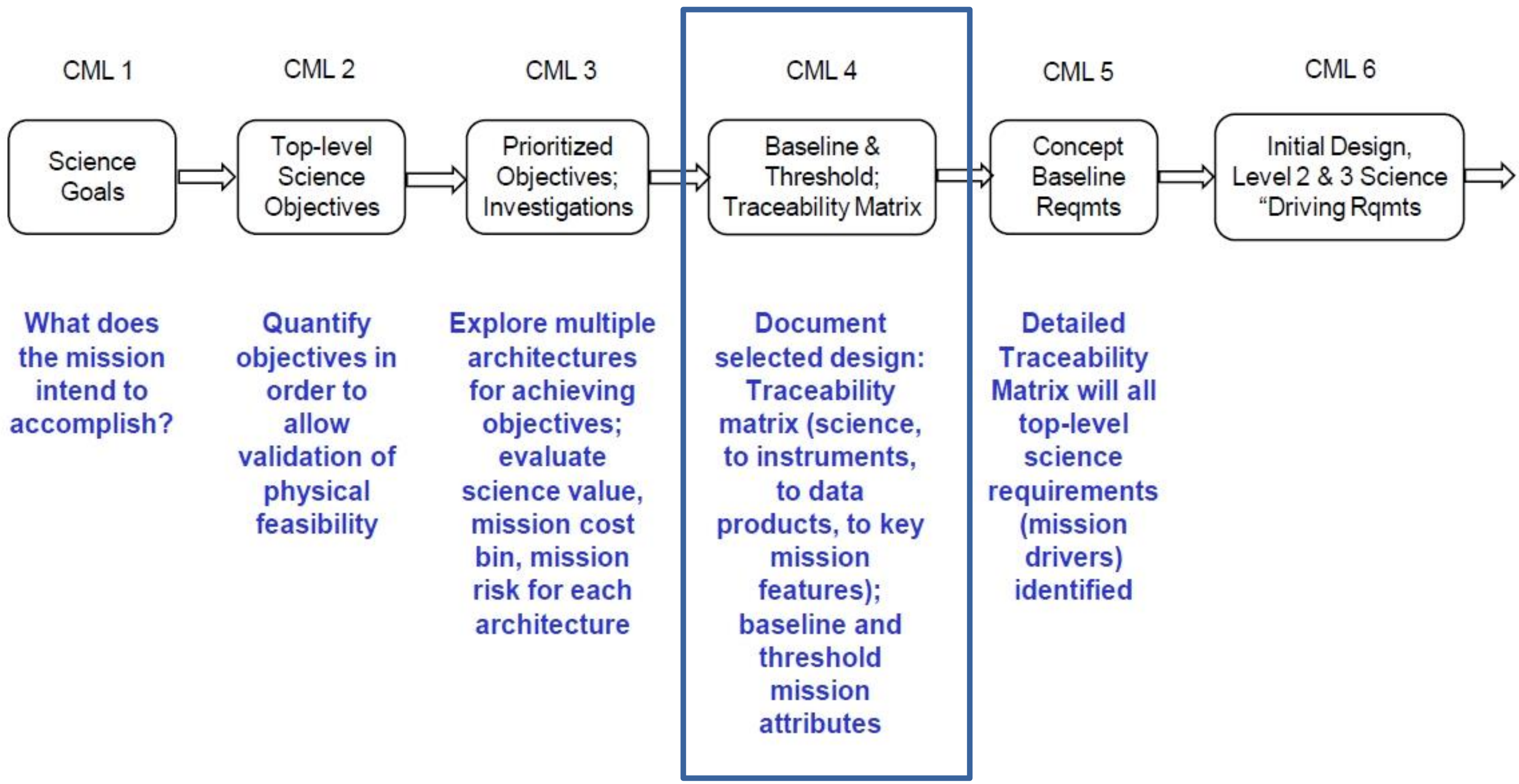
- TRL has become a universal language
  - Commonly used in AOs, briefings, conference sessions, peer-reviewed literature
  - NPR 7120.8 defines NASA-wide standard
  - "TRL 6 by PDR"
- ***TRL sets expectations despite variations in interpretation***

Technology Readiness Level (TRL) of an **enabling technology** at the time of Decadal submittal and how it will reach a TRL of 5 by KDP-B and TRL 6 by PDR will be an important factor to the Decadal Committee and independent cost/risk assessment.

Requirements: Increasing depth with increasing CML

-Prove mission *Feasibility* with respect to technical, cost, and risk resources
-Study Teams should address the “mission cost vs. science capability”

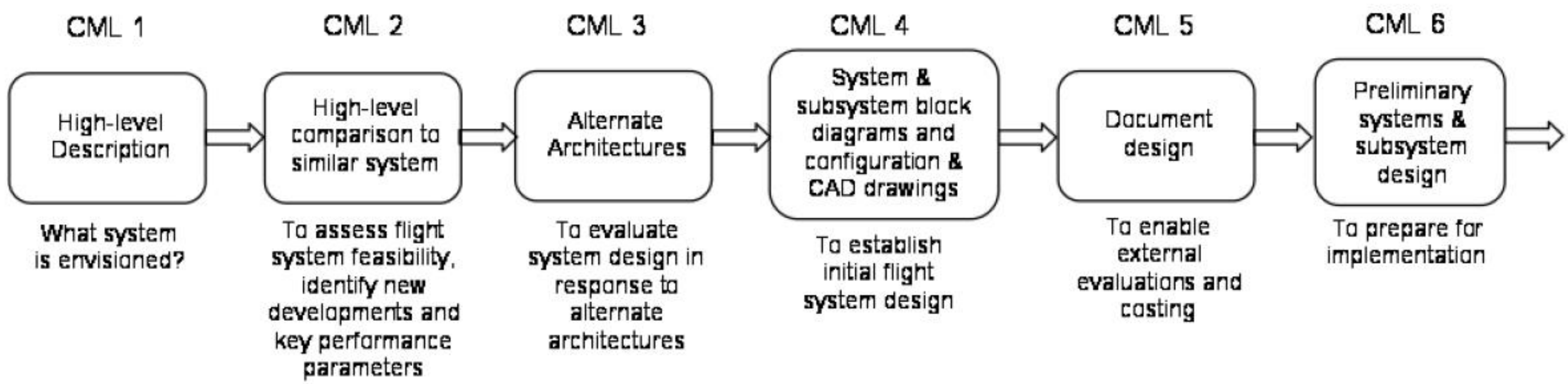
5.1.3 Science Objectives & Driving Requirements



Spacecraft Design: Increasing depth and detail with increasing CML

5.5 Spacecraft & Instrument System Design

Spacecraft & instrument system design is based on Level 3 and 4 requirements. It is defined through a series of trade studies and continues to mature from a high level architecture to detailed design through the System Critical Design Review in Phase C.



Study Success Criteria (2 of 2)

- **The final study deliverable shall be at a tailored CML 4, termed the "Decadal CML 4", as defined in the detailed table in backup charts**
  - CML2, 3, and 4 columns in the backup are all tailored for the Decadal Study
- **High Level Definitions of Maturity Levels:**
  - ***CML 2 Initial Feasibility:*** The mission concept and high-level objective are defined and questioned on the basis of feasibility, from a science, technical, and programmatic viewpoint. Lower-level objectives have been specified, key performance parameters quantified, and basic calculations have been performed. These calculations, to first order, determine the viability of the concept.
  - ***CML 3 Trade Space:*** Exploration has been done around the science objectives and architectural trades between the spacecraft system, ground system, and mission design to explore impacts on and understand the relationship between science return, cost, and risk.
  - ***Decadal CML 4 (Tailored CML-4):*** *Point Design.* A specific design and cost that returns the desired science has been selected within the trade space and defined down to the level of major subsystems with acceptable margins and reserves. Trades have been performed for selective, high-leverage subsystems

ExEP

ExoPlanet Exploration Program

Study Deliverables

All products delivered to APD Deputy Division Director

PCOS Physics of the Cosmos Program

NASA

COR Cosmic Origins Program

M1 Comments on Study Requirements and Deliverables — **April 29 2016[1]**

- Accept the study requirements/deliverables and submit plan--- or
- Provide rationale for modifying requirements/deliverables

O1 Optional: Initial Technology Gap Assessment — **June 30 2016**

- *To impact PCOS/COR/ExEP 2016 technology cycle*

M2 Detailed Study Plan **"Science Path" Survey Is Important to Moving Forward!** — **August 26 2016**

- Document starting point CML
- Deliver detailed study plan for achieving Decadal CML
- Deliver resource required to meet the deliverables for the study duration
- Deliver schedule to deliver milestones

M3 Complete Concept Maturity Level 2 Audit — **February 2017[2]**

- Identify, quantify and prioritize technology gaps for 2017 technology cycle

O2 Optional: Update Technology Gap Assessments — **June 2017**

M4 Interim Report — Early **Dec 2017[2]**

- Substantiate achieving Concept Maturity Level 3
- Deliver initial technology roadmaps; estimate technology development cost/schedule

M5 Update Technology Gap Assessments — **June 2018**

- In support of 2018 technology cycle

M6 Complete Decadal Concept Maturity Level 4 Audit and Freeze Point Design — **August 2018**

- Support independent cost estimation/validation process

M7 Final Report — **January 2019**

- Finalize technology roadmaps, tech plan and cost estimates for technology maturity

M8 Submit to Decadal — **March 2019**

[1]APD will provide final study requirements by May 2016 (see "Near Term Activities")

[2]Timed to influence following NASA budget cycle

National Aeronautics and Space Administration

X-Ray Surveyor Design Study: Based on Astrophysics Roadmap Science Objectives

MSFC Advanced Concept Office

July 2015

What CML did we achieve?

Table of Contents

Study Participants

Study Lead: Andrew Schnell (ED04)
Study Lead *Emeritus*: Randy Hopkins (ED04)

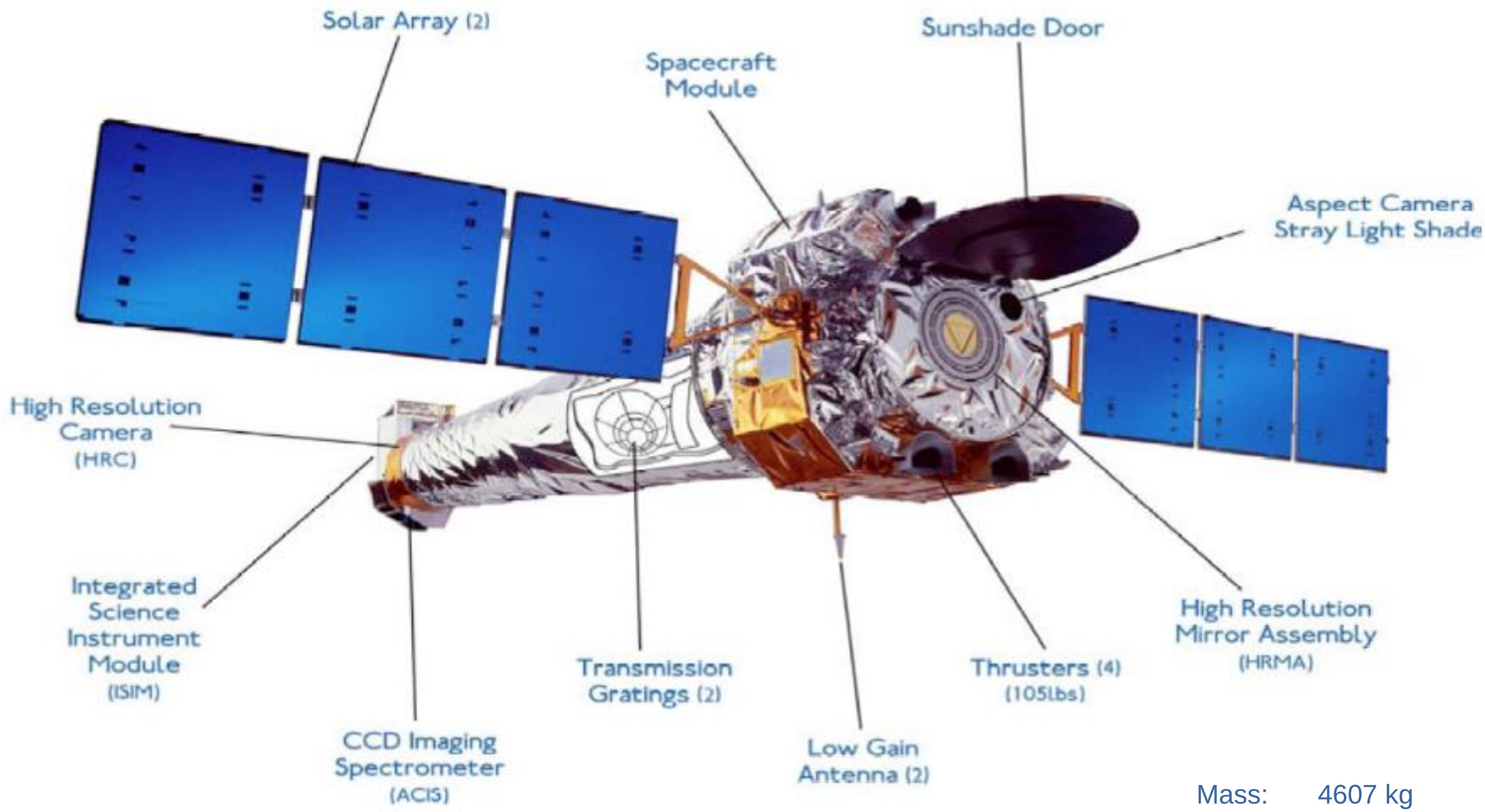
Mission Analysis	Dan Thomas (ED04)
	Randy Hopkins (ED04)
Configuration	Mike Baysinger (ED04)
Propulsion	Dan Thomas (ED04)
Power	Leo Fabisinski (ED04)
C&DH	Ben Neighbors (ES12)
Communications	Ben Neighbors (ES12)
GN&C	Robert Kinsey (ASC)
Thermal Analysis	Andrew Schnell (ED04)
Structural Analysis	Jay Garcia (ED04)
Mechanisms	Alex Few (ES21)
Environments	Joe Minow (EV44)
Cost	Spencer Hill (CS50)

Science: Jessica Gaskin (ZP12)
Martin Weisskopf (ZP12)

Simon Bandler (GSFC)
Mark Bautz (MIT)
Dave Burrows (PSU)
Abe Falcone (PSU)
Fiona Harrison (CalTech)
Ralf Heilmann (MIT)
Sebastian Heinz (UWM)
Caroline Kilbourne (GSFC)
Chryssa Kouveliotou (GWU)
Ralph Kraft (SAO)
Andrey Kravtsov (U-Chicago)
Randall (McEntaffer) U-Iowa)

Priyamvada Natarajan (Yale)
Steve O'Dell (ZP12)
Robert Petre (GSFC)
Andrew Ptak (GSFC)
Brian Ramsey (ZP12)
Paul Reid (SAO)
Dan Schwartz (SAO)
Harvey Tananbaum (SAO)
Leisa Townsley (PSU)
Alexey Vikhlinin (SAO)

Design Could Follow Chandra: Similar X-Ray Observatory



Attribute	CML 3	CML 4
Inheritance	Early evaluation of inheritance options, benefits, and risks across trade space	Discuss all significant heritage assets used by the design reference mission

Mass: 4607 kg
121 kg unused reserve

Power: 2900 W actual at launch
1350 used
2100 W EOL spec (5 yr)
2000 actual (14 yr)
1100 used

Design Approach

- Custom bus design
- Optimize all subsystems based on analysis from the discipline experts using appropriate tools
  - Makes the cost estimate more straightforward – if we modified an existing bus, determining the cost of modifications could be difficult

Margin Philosophy	
Spacecraft subsystems mass	30%
Payload mass	30%
Spacecraft power	30%
Payload power	30%
Cost	See Cost section

Attribute	CML 3	CML 4
Technical Margins	Use institutional margins where applicable. Analyze best and worst case scenarios	Critical performance margins estimated, resource margin estimated for design reference mission (AIAA S-120margin policies followed)

General Mission Requirements

Requirement	Requirement (Goal)	
Launch Year	2030	
Spacecraft Lifetime	5 years	
Consumables	20 years	
Orbit	SE-L2 or Chandra-type **Trade Study (Thermal, radiation, etc…)**	
Risk Class	B (assumed for baseline design). (as defined by NASA NPR-8705.4, *Risk Classification for NASA Payloads*.)	
Pointing	Radial	Roll (boresight)
Accuracy	30 arcsec	study output (see GN&C)
Knowledge (Derived requirement)	4 arcsec (p/y) RMS 99%	study output (see GN&C)
Stability	1/6 arcsec per 1 sec	study output (see GN&C)
Dithering	Lissajous figure, up to +/- 30" amplitude with 8 bits resolution; periods 100 to 1000 seconds subject to derived rate constraint; arbitrary phase (8 bits: amplitude, rate and phase are to be independently commanded in yaw and pitch.*	

* Rationale is to allow calibration to be averaged over a set of pixels, instead of calibrating every single pixel individually, AND to allow filling in what might be small gaps between elements in a focal plane array.

General Mission Requirements

Requirement	Requirement (Goal)
Slew rates for normal observing (and #/day)	90 deg/30 minutes**
Slew rates for TOO* (and #/day)	1 TOO per week. Slew rates same as above.
Continuous observation time	100000 s**
Downlink frequency	1 – 3 downlinks per day
Data downlink volume per day	240 Gbits (flexible, want to save cost; are there breakpoints?)
Data storage requirement	Sufficient for 48 hours of data
Data processing/compression	Assume that instruments provide data processing/compression. Spacecraft only provides storage for data to be downlinked.
Avoidance angles	
Sun	45 degrees; but the rest of the sky must be accessible (this may affect the solar array articulation mechanisms)
Other	na (We aren't doing a sky coverage analysis, so only the sun avoidance angle will affect the design to first order)
Door operation	Once open, does not need to close again.

* Target of Opportunity: an unscheduled observation of interest, such as a sudden X-ray emission from an interstellar or intergalactic source.

** Not a primary driver for design; can pause observation for momentum unloading if necessary.

Launch Vehicle Selection and Performance Estimates

Performance for Chandra-type orbit is from NASA Launch Services (NLS).
Performance for L2 transfer orbit is from NLS website.

Source -->	NLS quote		NLS website
Orbit type -->	**Elliptical Chandra-type**		**SE-L2 transfer**
Altitude or C3 -->	**16000 x 133000 km**		**C3 = -0.7 km2/s2**
Burn profile -->	2-burn	**3-burn**	**185 km parking orbit**
Atlas V 521	3355	**3305**	**4250**
Atlas V 531	3995	**3950**	**5005**
Atlas V 551	TBD	**4585**	**6185**
Falcon 9 (v1.1)	not requested	**not requested**	**3715**

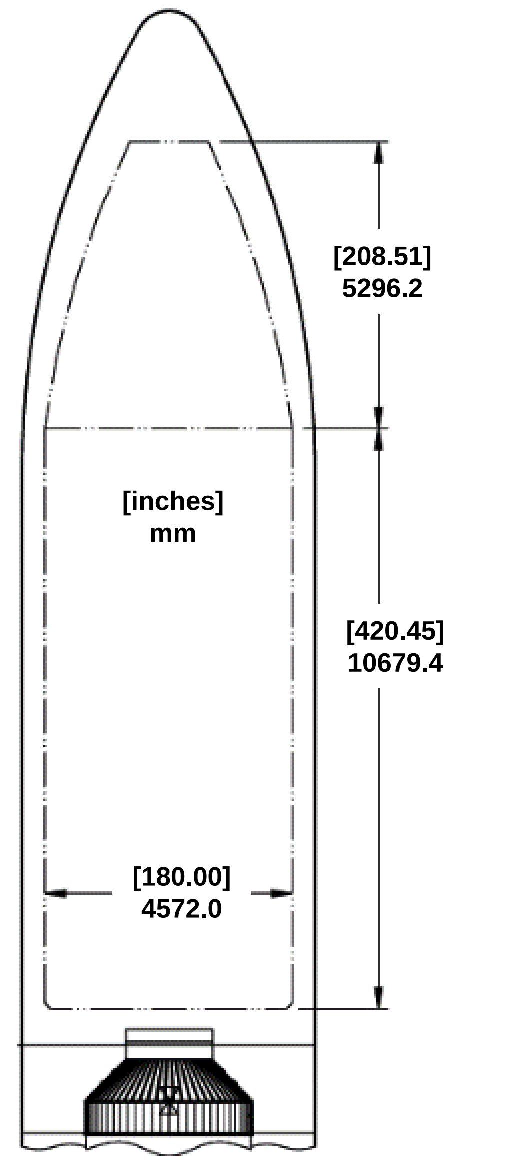
max

Ascent timeline for Chandra-type orbit was provided by NLS, and is included in the backup section but not included here since the performance to that orbit is inadequate for this mission.

Ascent timeline for SE-L2 estimated from data available in *Atlas V Launch Services Users Guide*. Eclipse time from JWST publications and ATLAST. Estimates are worst case, and assume eclipse occurs immediately after Earth departure burn.

	SE-L2 transfer	
Ascent/departure phase	**Duration**	**Source**
Launch to parking orbit insertion	30	Users Guide
Coast in parking orbit	90	Orbital period
Departure burn	6	Calculations
Coast to spacecraft separation	3	Users Guide
TOTAL TIME TO SEPARATION	**129 minutes**	
Eclipse period*	180	JWST/ATLAST
TOTAL ELAPSED TIME to SUNLIGHT	**309 minutes**	

*** NOTE: restricting launch window to two periods per year can eliminate this eclipse.**

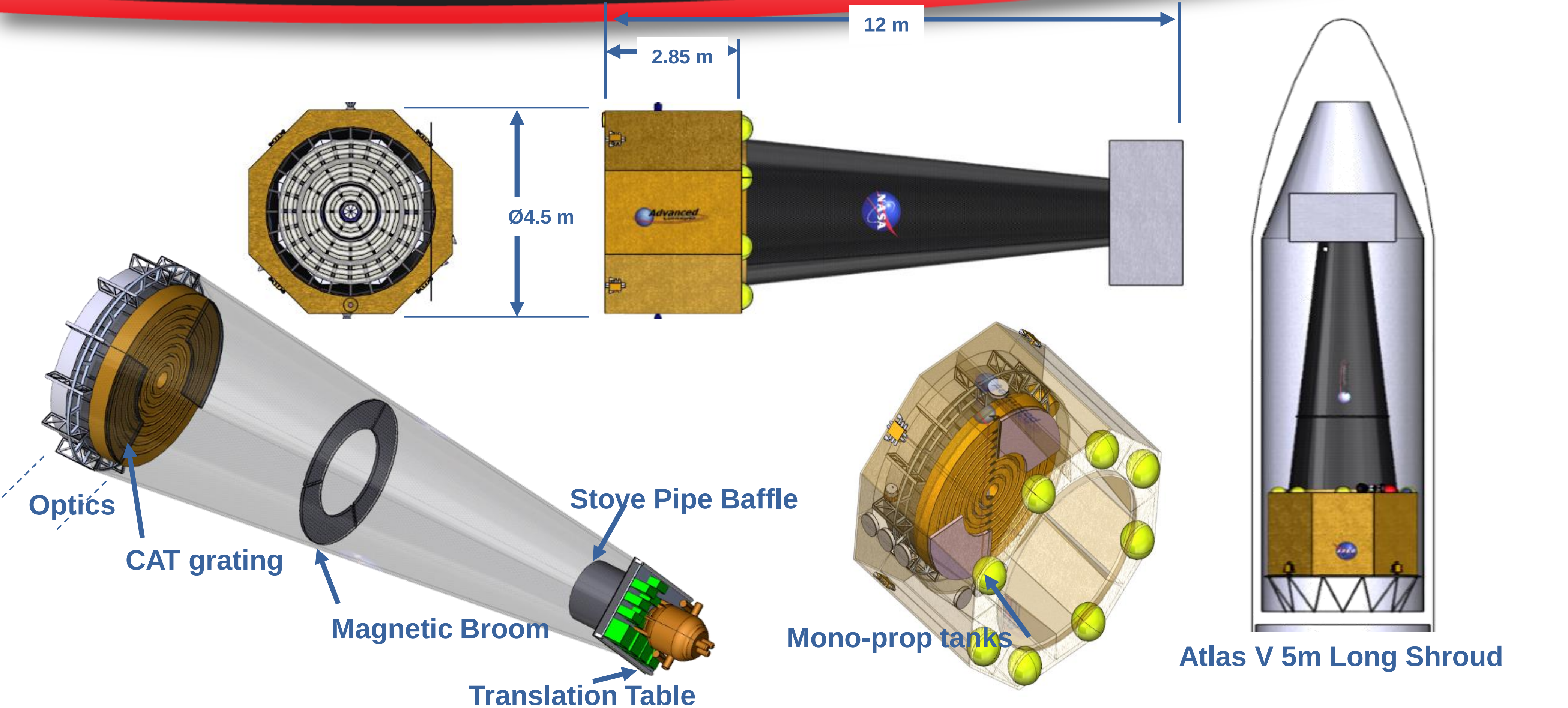


5m long shroud

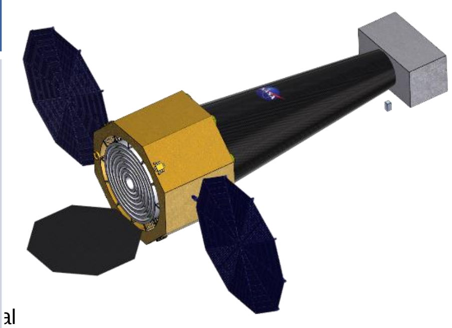
Relevant CML Attributes

Attribute	CML 3	CML 4
Science Data System	Science data rates and volume included in trade space analysis	Design reference science data sized to support data system flowdown requirements
Mission Development	Alternative set of mission architectures evaluated against science objectives, cost and risk Quantitatively bounded hazards of space environment	Design reference mission defined, including driving requirements, initial high-level scenarios, timelines and operational modes, mass, delta-V, and power estimates; telecom and data processing approach defined to mission flowdown requirements
Launch Services	Perform trades for candidate launch vehicles demonstrating compatibility with performance and fairing size	Preliminary launch vehicle(s) selection documented (NASA Launch Services used)

Observatory Configuration



Attribute	CML 3	CML 4
Spacecraft System Design	Unique features that distinguish one flight system architecture from another evaluated. Perform sensitivity studies to bound performance within trade space performed.	Spacecraft systems architecture for design reference mission defined with mechanical configuration drawings to support spacecraft flowdown requirements

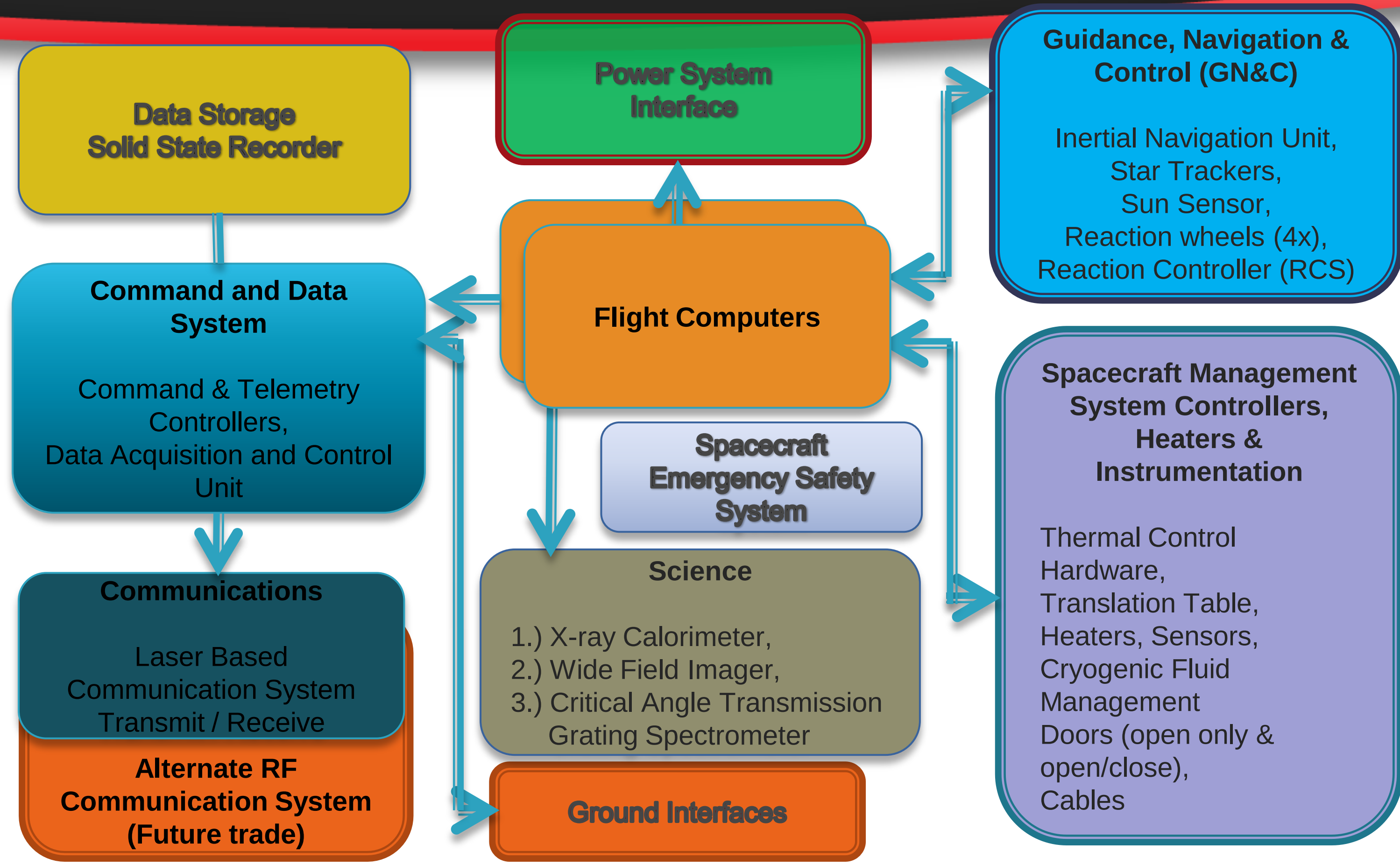


Mass Summary

X-Ray Surveyor		Basic Mass (kg)	Contingency (%)	Contingency (kg)	Predicted Mass (kg)
1.0	Structures	795.60	30%	238.68	1034.28
2.0	Propulsion	127.26	30%	38.18	165.43
3.0	Thermal	38.00	30%	11.40	49.40
4.0	Avionics	97.64	30%	29.29	126.93
5.0	GN&C	156.76	30%	47.03	203.79
6.0	Power	426.00	33%	140.40	566.40
7.0	Science Instrument Module (Translation Table)	201.00	30%	60.30	261.30
	Dry Mass	*1842.26*	*30%*	*552.68*	*2394.93*
8.0	Non-Propellant Fluids	32.08	0%	0.00	32.08
9.0	Telescope	1840.90	30%	552.27	2393.17
10.0	Science Instruments	520.80	30%	156.24	677.04
	Inert Mass	*2393.78*		*708.51*	*3102.29*
	Propellant	*494.90*			*494.90*
	Vehicle Mass	**4730.94**		**1261.19**	**5992.13**

Attribute	CML 3	CML 4
Master Equipment Lists	Mass of major elements quantified based on subsystem estimates	MEL documented for design reference mission to assembly level (e.g., antenna, propellant, tank, star tracker, etc…)

Architecture and Interfaces



Attribute	CML 3	CML 4
Ground System / Mission Operations System Design	Mission ops drivers and sensitivities addressed. Major flight / ground trades identified. New ground system capabilities identified.	Mission Operation System / Ground Data System architecture for design reference mission to support the con-ops described.

Cost Estimates

- Instrument/optics are assumed to be TRL 6 or better prior to phase B
- Mass and power margins set to 30%
- Cost margins set to 35% except for instruments
- Instruments costed at 70%-confidence using NASA Instrument Cost Model (NICM)
- Costs in FY 15$

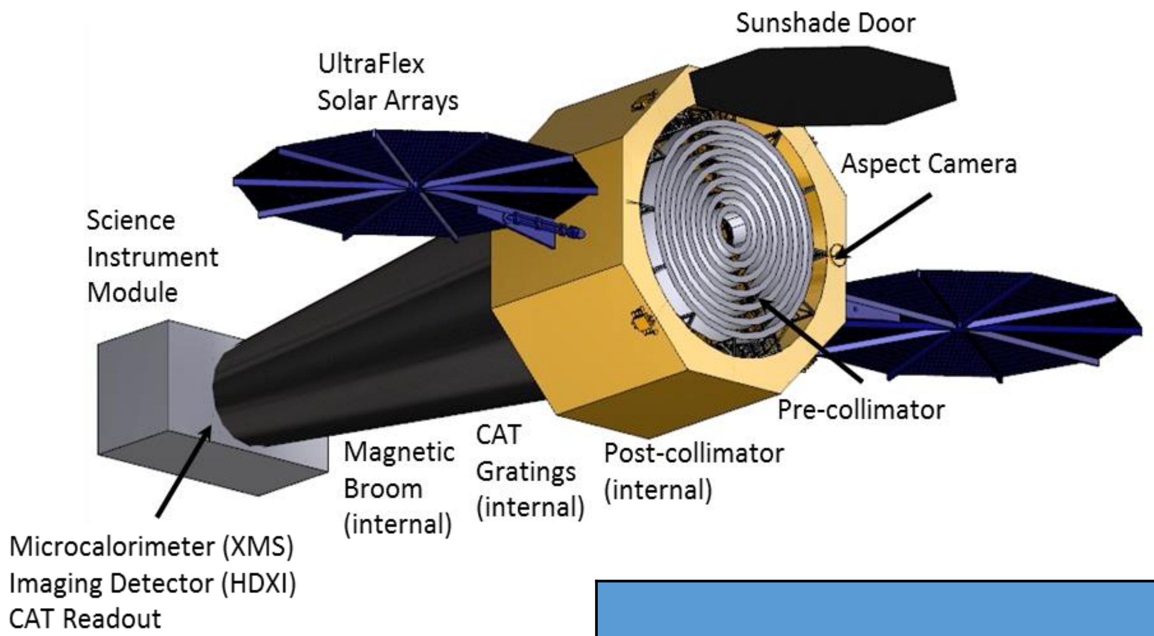
Spacecraft	$1,650M
X-ray Telescope Assembly	$ 489M
Scientific Instruments	$ 377M
Pre-Launch Operations, Planning & Support	$ 196M
Launch Vehicle (Atlas 551)	$ 240M
Total	**$2,952M**
Mission Operations	$45M/yr
Grants	$25M/yr

Attribute	CML 3	CML 4
Cost Estimation and Cost Risk	Cost sensitivities explored across trade space as a function of major drivers Initial estimate down to level 2 and level 3 for spacecraft and payload Cost uncertainty quantified System cost risks identified	Cost estimate and basis of estimate provided for design reference mission Cost uncertainty quantified Cost risks identified at subsystem level, with emphasis on enabling technologies

Instrument/Technology CML Attributes

Attribute	CML 3	CML 4
Instrument System Design	Key instrument performance requirements, measurement techniques and instruments selected against science / mission objectives, cost and risk Sensitivity studies to bound performance within trade space performed	Instrument system architecture for design reference mission defined with mechanical configuration drawings and block diagrams to support instrument flowdown requirements and performance simulations Instrument performance requirements traced to scientific requirements
Technology	Compare technologies and major developments required for design options across trade space	Technology options described Baseline options selected and justified (technology roadmap) Rationale for TRL(s) explained Risk mitigations for all new technologies identified

X-Ray Surveyor Payload



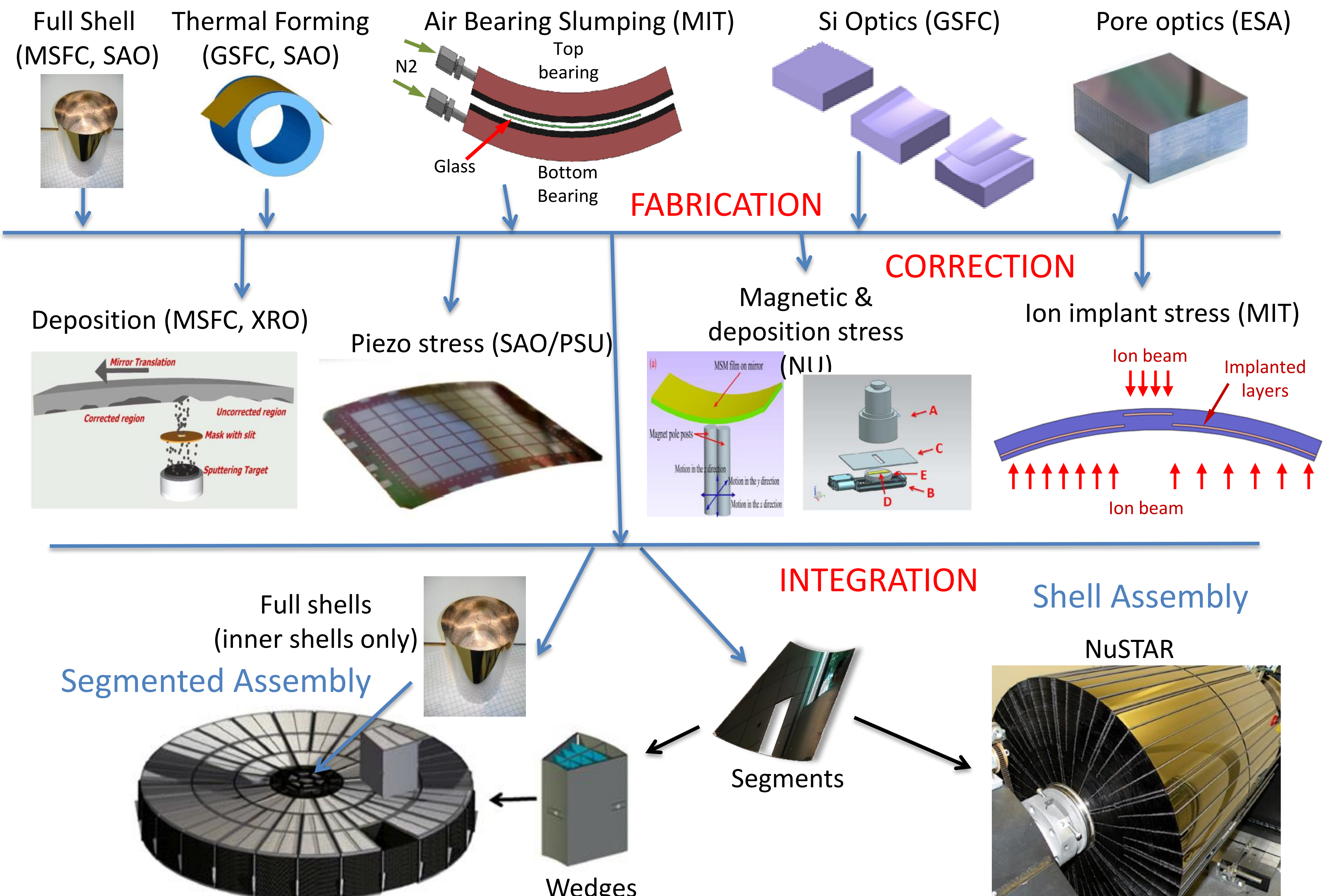
- High-resolution X-ray telescope
- Critical Angle Transmission XGS
- X-ray Microcalorimeter Imaging Spectrometer
- High Definition X-ray Imager

Concept Payload for:

- Feasibility (TRL 6)
- Mass
- Power
- Mechanical
- Costing

	Chandra	X-Ray Surveyor
Relative effective area (0.5 – 2 keV)	1 (HRMA + ACIS)	50
Angular resolution (50% power diam.)	0.5”	0.5”
4 Ms point source sensitivity (erg/s/cm^2)	5×10^{-18}	3×10^{-19}
Field of View with < 1” HPD (arcmin^2)	20	315
Spectral resolving power, R, for point sources	1000 (1 keV) 160 (6 keV)	5000 (0.2-1.2 keV) 1200 (6 keV)
Spatial scale for R>1000 of extended sources	N/A	1”
Wide FOV Imaging	16’ x 16’ (ACIS) 30’ x 30’ (HRC)	22’ x 22’

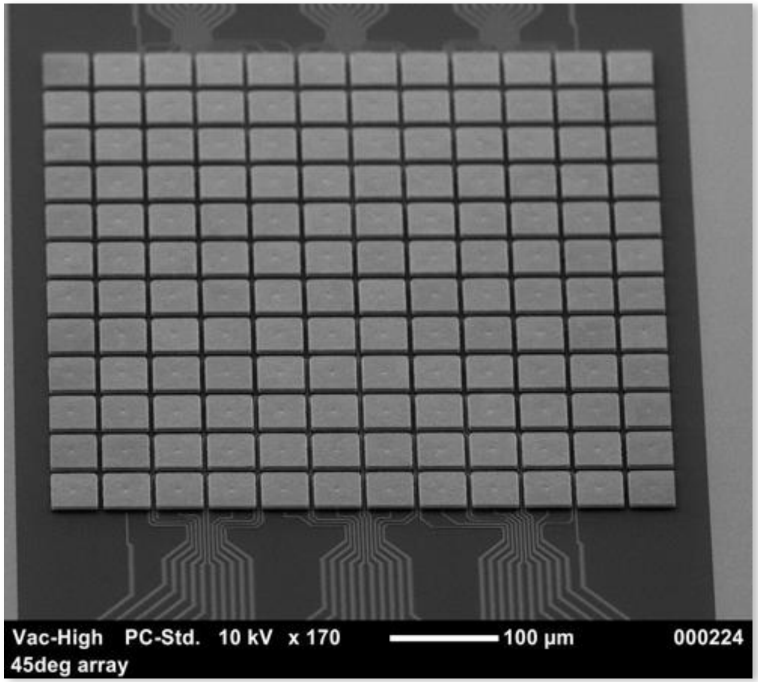
Taxonomy of X-ray Telescope Fabrication

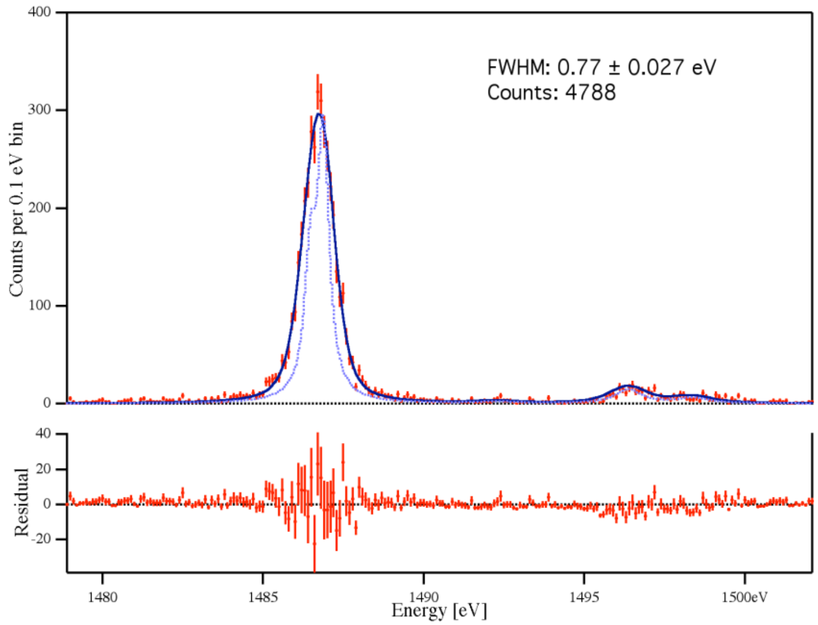


Thanks to Dan Schwartz

X-ray Microcalorimeter Imaging Spectrometer

Parameter	Goal
Energy Range	0.2 – 10 keV
Spatial Resolution	1 arcsec
Field-of-View	5 arcmin x 5 arcmin (min)
Energy Resolution	< 5 eV
Count Rate Capability	< 1 c/s per pixel
Pixel Size / array size (10-m focal length)	50 µm pixels / 300 x 300 pixel array



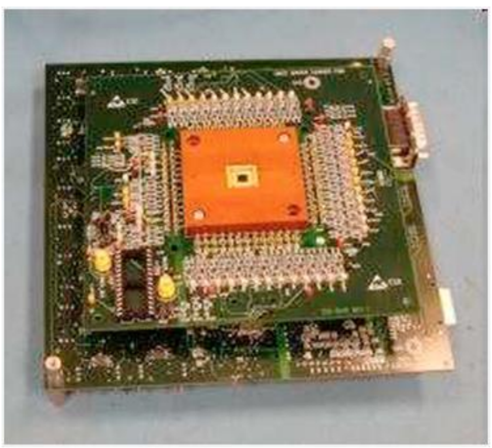


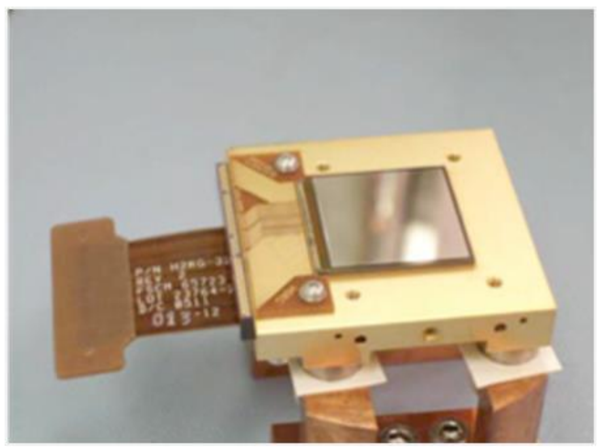
__Challenge:__ Develop multiplexing approaches for achieving ~10^5 pixel arrays

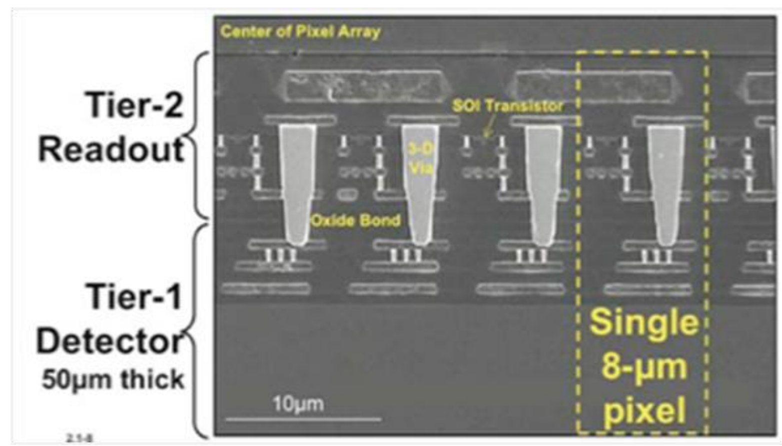
High Definition X-ray Imager

Parameter	**Goal**
Energy Range	0.2 – 10 keV
Field of View	22 arcmin x 22 arcmin
Energy Resolution	37 eV @ 0.3 keV, 120 eV @ 6 keV (FWHM)
Quantum Efficiency	> 90% (0.3-6 keV), > 10% (0.2-9 keV)
Pixel Size / Array Size	<16 µm (< 0.33 arcsec/pixel) / 4096 x 4096 (or equivalent)
Frame Rate	> 100 frames/s (full frame) > 10000 frames/s (windowed region)
Read Noise	< $4e^-$ rms

All have been demonstrated individually


SAO/Sarnoff


PSU/Teledyne



MIT/Lincoln Lab

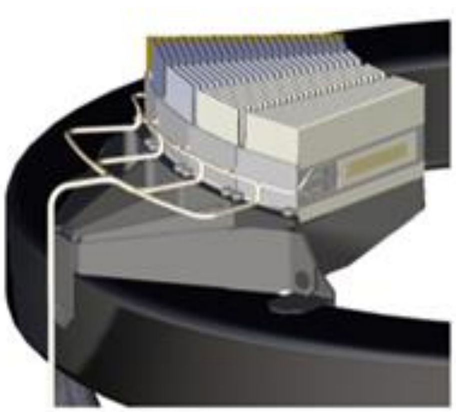
<u>Challenges</u>: Develop sensor package that meets all requirements, and approximates the optimal focal surface

Grating Spectrometer

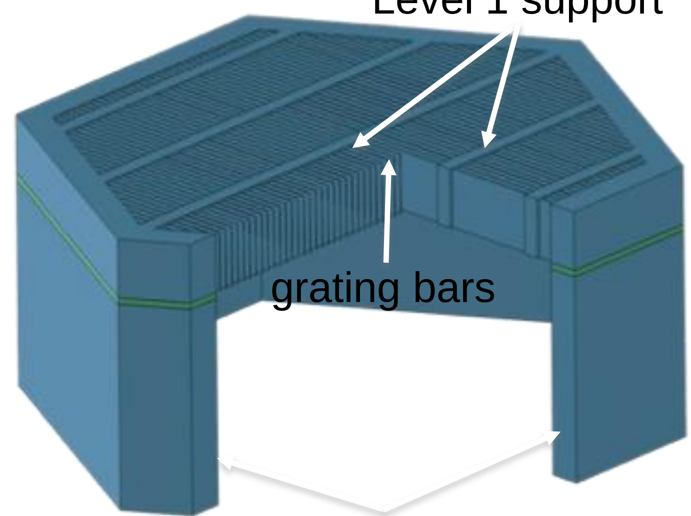
- Resolving power = 5000 & effective area = 4000 cm^2
- Energy range 0.2 – 2.0 keV

Blazed Off-Plane Reflection gratings

(Univ. of Iowa)



Critical Angle Transmission (CAT) gratings (MIT)



Challenges: improving yield, developing efficient assembly processes, and improving efficiency

CML Attributes Not Covered

Attribute	CML 3	CML 4
Technical Risk Assessment & Management	Compare risks across the various architectures Identify mitigation strategies for key risks	Risk drivers listed 5x5 matrix provided with relevant risk drivers (include selected mitigation / development options)
System Engineering	Capture the relative merits of performance, cost and technical risk over a broad range of architectures Subsystem dependencies identified	Selective, high-leverage science, spacecraft, and ground system trades completed
Verification & Validation	Identify any major or unique V&V activities	Approach for verifying new and enabling functions of the design reference mission defined to support an acceptable risk assessment by independent reviewers System testbeds and prototype models identified where applicable
Schedules	Assess variations and risks to science, development schedule and impacts to mission duration	Top-level schedule (one page) developed for design reference mission to support (coarse) independent cost estimates
Work Breakdown Structure	NASA standard WBS & Dictionary (down to level 2 for level 3 for spacecraft and payload) used	N/A