Implications of adopting 5 arcsec angular resolution

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Background

- Project team agreed to investigate system level implications of changing angular resolution requirement from 15 arcsec (HPD) to 5 arcsec at February FST meeting
- Goal was to report at next FST meeting
- Project team performed top level study in March-May 2008. Participants included Jay Bookbinder, Rich Kelley, Caroline Kilbourne, Paul Reid, Mark Freeman, Will Zhang, Diep Nguyen, Jean Grady, and Tom Buckler
- Report to project submitted June 2008
- Subsequently, two important decisions were made:
  - Change the resolution requirement
  - Move to a 1 mirror configuration, in conjunction with creation of IXO mission
- Still critical to the project to understand and communicate the implications of the angular resolution change to the configuration and various subsystems
- Presentation factors in change to new, single mirror configuration
  - Significant implications for many aspect of mission but not for angular resolution issue

Methodology

- Significant limitation - much is still unknown about the configuration
  - there is no FMA conceptual design with sufficient detail to make quantitative studies
  - Many of the quantities in the angular resolution error budget are based solely on engineering judgment, and need verification
- Still, best starting point is with the error budget; this methodology is robust despite substantial configuration change
- We identified the crucial differences between the 5 arcsec and 15 arcsec error budgets
- We then determined (largely qualitatively) what kinds of changes the tighter error budget terms would require - optical, mechanical, thermal, attitude - and how changes might affect mission cost, schedule and complexity
- Major changes will be quantified as configuration becomes better defined

The 15 arcsec error budget

	Single mirror + calorimeter Angular Resolution Error Budget - 15"										
	ITEM (HPD - arcsec)	RQMT	Margin		Allocation						RATIONALE
1	Calorimeter Imaging Resolution	15.00	6.16								1 SXT
2	On-Orbit Single Telescope			13.67							RSS
3	Calorimeter pixelization error				2.78						3 arc-second pixels, with sub-pixel resolution
1a	Telescope Resolution (independent of detector type)			13.39							RSS
4	Telescope level effects				4.80						RSS
5	Image Reconstruction errors (over obs)					4.24					RSS
6	Attitude knowledge drift						3.00				Chandra experience
7	FMA/detector relative drift (thermal)						3.00				Chandra experience - includes FID light system
8	FMA/detector vibration effects					2.00					Chandra experience (jitter)
9	FMA/detector misalignment (off-axis error)					1.00					Calc: field dependent aberration due to +/- 30 arc-sec alignment
10	FMA/detector Focus Error					0.20					Allocation - includes focal plane focus adjustment
11	FMA On-orbit performance				12.50						RSS
12	SXT Mirror launch shifts					2.00					Eng est based on Chandra
13	On-orbit Thermally Driven Errors					2.24					RSS
14	Bulk temperature effects						1.00				Engineering judgement for +/- 1 C
15	Gradient effects						2.00				Engineering judgement for 1C gradient
16	Material Stability					1.00					Est based on Chandra work
17	FMA/Telescope mounting strain					1.00					Eng estimate based on Chandra experience
18	FMA, As built					12.05					RSS
19	Gravity Release						1.50				FEA Analysis using vertical assy
20	Bonding Strain						2.00				Allocation
21	Module to Module alignment						2.00				Allocation
22	Module						11.62				RSS
23	Distort. & misalign due to module packing							3.54			Allocation
24	Mirror Pair Co-alignment							0.71			Allocation
25	Mirror Pair							11.04			RSS
26	P-S alignment in module								3.38		RSS
27	Alignment Metrology Dynamic Accuracy									0.76	Allocation - Based upon Chandra CDA alignment metrology
28	Alignment Metrology Static Accuracy									1.68	Allocation - Based upon Chandra CDA alignment metrology
29	Thermal Drift									2.00	Allocation - Based upon Chandra experience
30	Focus and Coma Alignment									2.00	Allocation
31	Segment Installation in module								3.54		Allocation
32	Segment Pair (P-S)								9.90		Est based on tech dev program to date
	Color Code	Rqmt		Margin		RSS Predict			Allocation		

- Mirror terms dominate error budget, particularly the individual segment surfaces
- No need for focus mechanism or fiducial system

The 5 arcsec error budget

	Single mirror + calorimeter Angular Resolution Error Budget - 5"										
	ITEM (HPD - arcsec)	RQMT	Margin	Allocation							RATIONALE
1	Calorimeter Imaging Resolution	5.00	0.62								1 SXT
2	On-Orbit Single Telescope			4.96							RSS
3	Calorimeter pixelization error				0.96						3 arc-second pixels, with sub-pixel resolution
1a	Telescope Resolution (independent of detector type)			4.87							RSS
4	Telescope level effects				1.51						RSS
5	Image Reconstruction errors (over obs)					1.41					RSS
6	Attitude knowledge drift						1.00				Chandra experience
7	FMA/detector relative drift (thermal)						1.00				Chandra experience - includes FID light system
8	FMA/detector vibration effects					0.20					Chandra experience (jitter)
9	FMA/detector misalignment (off-axis error)					0.05					Calc: field dependent aberration due to +/- 30 arc-sec alignment
10	FMA/detector Focus Error					0.50					Allocation - includes focal plane focus adjustment
11	FMA On-orbit performance				4.63						RSS
12	SXT Mirror launch shifts					0.50					Eng est based on Chandra
13	On-orbit Thermally Driven Errors					1.41					RSS
14	Bulk temperature effects						1.00				Engineering judgement for +/- 1 C
15	Gradient effects						1.00				Engineering judgement for 1C gradient
16	Material Stability					1.00					Est based on Chandra work
17	FMA/Telescope mounting strain					1.00					Eng estimate based on Chandra experience
18	FMA, As built					4.14					RSS
19	Gravity Release						1.00				FEA Analysis using vertical assy
20	Bonding Strain						1.00				Allocation
21	Module to Module alignment						1.00				Allocation
22	Module						3.76				RSS
23	Distort. & misalign due to module packing							0.71			Allocation
24	Mirror Pair Co-alignment							0.71			Allocation
25	Mirror Pair							3.63			RSS
26	P-S alignment in module								1.12		RSS
27	Alignment Metrology Dynamic Accuracy									0.50	Allocation - Based upon Chandra CDA alignment metrology
28	Alignment Metrology Static Accuracy									0.50	Allocation - Based upon Chandra CDA alignment metrology
29	Thermal Drift									0.50	Allocation - Based upon Chandra experience
30	Focus and Coma Alignment									0.71	Allocation
31	Segment Installation in module								1.00		Allocation
32	Segment Pair (P-S)								3.30		Est based on tech dev program to date
	Color Code	Rqmt		Margin		RSS Predict			Allocation		

- Allocations subject to change as knowledge of systems is refined
- Mirror terms become comparable with rest of system
- All terms are at arc second order of magnitude, so major changes unlikely
- Some terms have been reduced by introduction of complexity (e.g., focus mechanism)

Identifying the major differences

	Comparison between 5 arcsec and 15 arcsec angular resolution error budgets (single mirror)						
	ITEM (HPD - arcsec)	15" allocation	5" allocation	Mass	Power	Complexity	Comment / Implication
1	Calorimeter Imaging Resolution	15.00	5.00				
2	On-Orbit Single Telescope	13.67	4.96				Current total allocation
3	Calorimeter pixelization error	2.78	0.96				3 arcsec pixels, with sub-pixel resolution
1a	Telescope Resolution (independent of detector type)	13.39	4.87				
4	Telescope level effects	4.80	1.51				
5	Image Reconstruction errors (over obs)	4.24	1.41				
6	Attitude knowledge drift	3.00	1.00	x	x	x	tighter ACS Specification - better trackers, gyros, quieter wheels?
7	FMA/detector relative drift (thermal)	3.00	1.00	x	x	x	Fiducial system required
8	FMA/detector vibration effects	2.00	0.20	x	x	x	tighter ACS Specification - better trackers, gyros, quieter wheels?
9	FMA/detector misalignment (off-axis error)	1.00	0.05	x	x	x	tighter ACS Specification - better trackers, gyros, quieter wheels?
10	FMA/detector Focus Error	0.20	0.50				3D focal plane adjustment required
11	FMA On-orbit performance	12.50	4.63				
12	SXT Mirror launch shifts	2.00	0.50	x			Stiffer structure
13	On-orbit Thermally Driven Errors	2.24	1.41				
14	Bulk temperature effects	1.00	1.00			x	Need closely CTE matched materials
15	Gradient effects	2.00	1.00			x	Gradients are controlled at module level
16	Material Stability	1.00	1.00				
17	FMA/Telescope mounting strain	1.00	1.00				
18	FMA, As built	12.05	4.14				
19	Gravity Release	1.50	1.00	x			Stiffer, more accurate FMA integration structure
20	Bonding Strain	2.00	1.00	x			Stiffer, more accurate FMA integration structure
21	Module to Module alignment	2.00	1.00	x			Stiffer, more accurate FMA integration structure
22	Module	11.62	3.76				
23	Distort. & misalign due to module packing	3.54	0.71	x		x	Stiffer, more accurate module housing
24	Mirror Pair Co-alignment	0.71	0.71			x	More accurate alignment process
25	Mirror Pair	11.04	3.63				
26	P-S alignment in module	3.38	1.12				
27	Alignment Metrology Dynamic Accuracy	0.76	0.50			x	More precise alignment facility
28	Alignment Metrology Static Accuracy	1.68	0.50			x	More precise alignment facility
29	Thermal Drift	2.00	0.50			x	Tighter environmental control during assembly/alignment
30	Focus and Coma Alignment	2.00	0.71	x		x	Stiffer, more accurate module housing; more precise alignment facility
31	Segment Installation in module	3.54	1.00	x		x	Stiffer, more accurate module housing; more precise alignment facility
32	Segment Pair (P-S)	9.90	3.30			x	3x better mandrels, lower microroughness, higher precision forming

- Allocations in green, RSS terms in red
- All major errors must be reduced by a factor of three

Significant consequences - mirror

Consequences to FMA components of angular resolution requirement change

	Technology Development	Production
Mandrels	Added time, expense to develop methodology for figuring and measuring.	Processing time per mandrel not completely defined for a 15-arcsec mirror. Number of additional cycles and processing time expected to be small for each mandrel. Possible cost increase if more precise metrology equipment is needed.
Segment forming	Sag must be improved by factor of 10, mid-frequency roughness by 3 over currently achieved values. Requires more stringent process control, and understanding of systematic and random errors. Possible unknown break points. Process development will take longer.	Unlikely to be substantially different from current expectation. Possible additional time/cost for mandrel treatment. Tighter environmental controls needed.
Fabrication metrology	Current metrology approach expected to be adequate. Mirror mount technique must be improved.	Tighter environmental controls needed Š facility cost impact.
Mounting/Alignment	Baseline approach needs to be developed.	Cannot assess impact because baseline approach not yet developed. A stiffer housing will be needed. CTE match requirements are likely to increase material cost and design complexity.

- **Primary consequence is need to extend technology development to demonstrate improved segment surfaces, develop mandrel production methodology, and refine mounting approach using materials with closer CTE match**
- **Cost per mandrel will probably not increase substantially, but the cost and duration of developing the mandrel production approach will likely increase.**
- **Significant additional technology development will be required to learn how to produce segments consistent with 5 arcsec. There could be issues that arise for 5 arcsec that do not affect 15 arcsec, but have not yet been encountered.**
- **Existing segment metrology should be adequate.**
- **Higher accuracy mounting and alignment will lead to higher cost (more precise fixtures, more expensive housing materials, longer time per alignment operation).**

Other significant consequences

- **Technology development: Largely associated with the mirror system (complexity, schedule).**
- **FMA optomechanical: Increased stiffness, possibly different (more expensive) materials; (mass, complexity).**
- **FMA thermal: Tighter thermal requirements (which need to be defined) will lead to a more complex thermal control system (complexity). Some relief due to thermal isolation of modules (thermal control at module level), but module components will need to be closely CTE matched.**
- **Obs. thermal: Tighter temperature range and gradients might be needed. The L2 orbit could reduce necessary changes (power, complexity).**
- **Obs. mechanisms: Focus mechanism will required (mass, power, complexity).**
  - **Needed as a result of introduction of EOB**
- **ACS: Fiducial system will be required (mass, power, complexity).**
- **I&T: Tighter initial alignment specifications, and thermal requirements (complexity, schedule).**
- **Operations/calibration: Additional complexity associated with fiducial system and mechanisms (complexity).**

Next steps

- Refine mirror technology roadmap, incorporating 5 arcsec as baseline
- Substantiate each error budget term, and revise as appropriate.
  - Most are based on analogy with Chandra and other missions.
  - Terms of most concern are related to FMA thermal and mechanical.
  - Modeling, analysis and/or measurements need to be performed for each term. This includes, but is not limited to:
    - Develop a more rigorous attitude reconstruction error budget. Verify by dynamical modeling of MDL configuration.
    - Verify jitter term - dynamical analysis of attitude jitter and vibration introduced by wheels and mechanical cooler
    - Complete FMA conceptual design, and use to verify related error terms
      - » Model thermal distortions and set T, ΔT limits
      - » Model mechanical distortions from mass loading, gravity release
    - Finite element and thermal modeling of observatory
      - » Verify stiffness and temperature range are appropriate
- Understand implications to error budget of adopting silicon pore optics