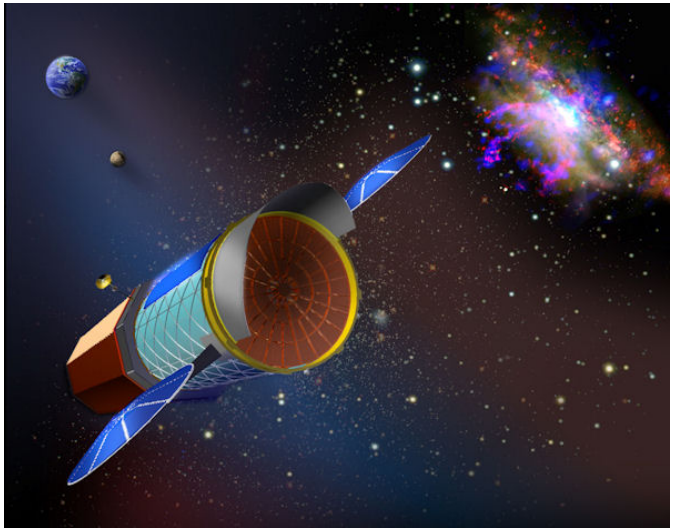
IXO Mission Systems Table Top Review

Introduction / Agenda



Jean Grady
IXO Project Manager

International X-ray Observatory (IXO) Mission Systems Table Top Review

Place, Date, and Time

- **GSFC, Bldg 23, Room C130D** *(the GLAST / JDEM Conference Room)*
- **Thursday, March 12, 2009, 9:00am to 4:00pm, 1 hr break for lunch**

Meet-Me (Voice)

- **1-877-916-0676 Passcode: 874553**

Webex

- **https://www.mymeetings.com/nc/join.php?i=742063039&p=constellationx&t=c**
- **Meeting Number: 742063039**
- **Password: constellationx**

Agenda

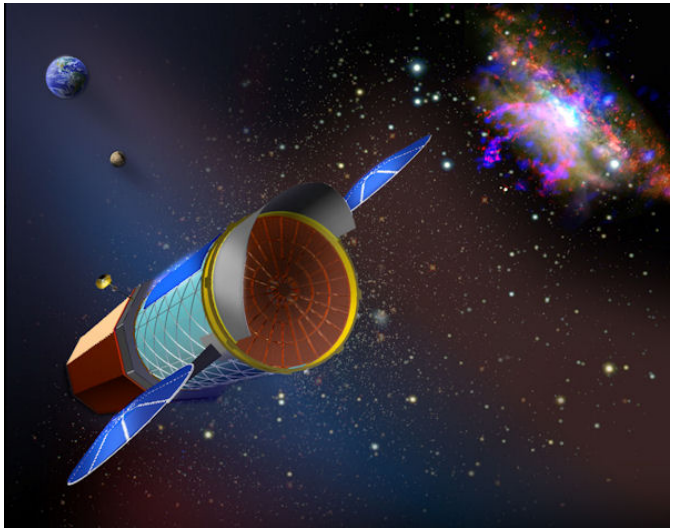
9:00 – 9:15	Introduction	Jean Grady	
9:15 – 10:15	IXO Overview *(for context only)*		
	- Science Overview	Rob Petre	10 min
	- Mission Overview	Gabe Karpati	10 min
	- Payload Overview		
	- Mirror (FMA) Overview	Mike Hill	10 min
	- Mirror (FMA) Mechanical Design	Dave Robinson	10 min
	- Instruments Overview	Tom Buckler	20 min
10:15 – 11:00	Systems Engineering	Gabe Karpati and Tony Nicoletti	
11:00 – 12:00	Structural / Mechanical	Dave Robinson	
12:00 – 1:00	*Lunch*		
1:00 – 2:00	Integrated Modeling	Dave Robinson and Gabe Karpati	
2:00 – 2:15	Flight Dynamics	Mike Mesarch (or Gabe Karpati)	
2:15 – 3:00	Pointing, Error Budgets	Gabe Karpati	
3:00 – 3:15	Observatory I&T	Steve Leete	
3:15 – 3:30	Operations	Jay Bookbinder	
3:30 – 4:00	Subsystems Overview	Gabe Karpati	
4:00 – 4:15	Closing Remarks	Review Team	

Review Panel

- Chair:
  - Mark Steiner
- Mission:
  - Art Whipple
  - Steve Scott
  - Mike Menzel
- Systems:
  - Tupper Hyde
  - Jamie Esper
  - John Oberright
- Payload:
  - Gary Sneiderman
  - Mark Freeman
  - Paul Reid
- GN&C:
  - Landis Markley (afternoon only)
  - Peiman Maghami
- Mechanical / Structural:
  - Rodger Farley
- Thermal:
  - Dan Nguyen

IXO Systems Table Top Review

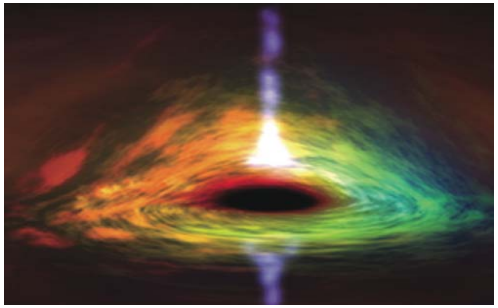
2009 03 12
NASA GSFC, Bldg 23, Room C130D



Science Overview

Rob Petre
Deputy Project Scientist - NASA
(for Nick White)

IXO Science Objectives



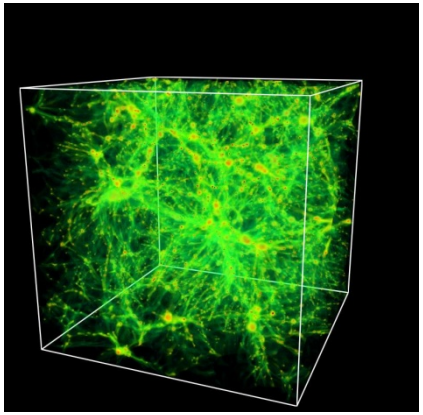
Black Hole growth and matter under extreme conditions

How do super-massive Black Holes grow and evolve?

What is the behavior of matter orbiting close to a Black Hole event horizons and does it follow the predictions of GR?

What is the equation of state of matter in Neutron Stars?

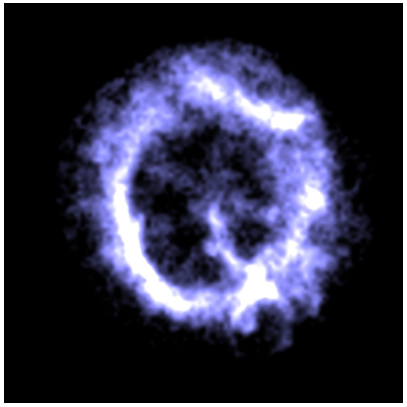
Galaxy Clusters, Galaxy Formation and Cosmic Feedback



What are the processes by which galaxy clusters evolve and how do clusters constrain the nature of Dark Matter and Dark Energy?

How does Cosmic Feedback work and influence galaxy formation?

Are the missing baryons in the local Universe in the Cosmic Web and if so, how were they heated and infused with metals?



The life cycles of matter and energy

How do supernovae explode and create the iron group elements?

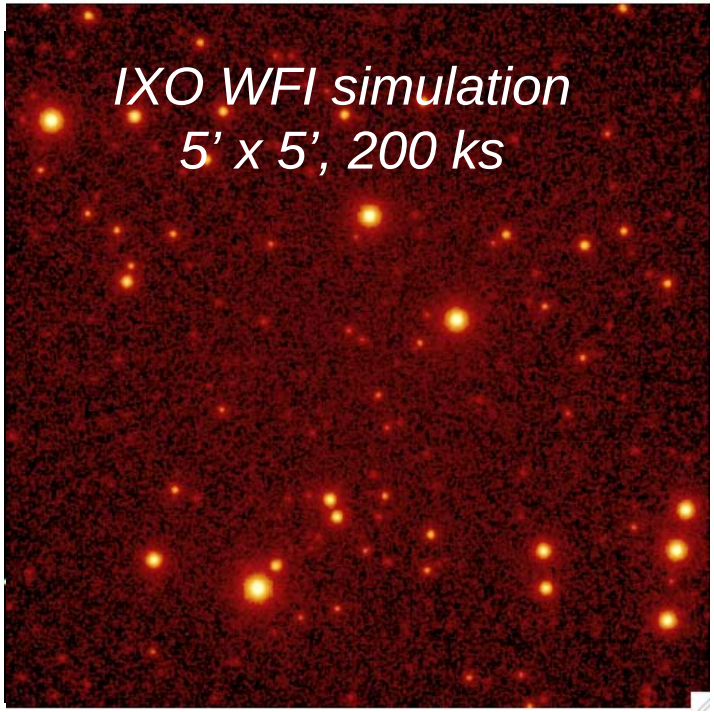
How do high energy processes affect planetary formation and habitability?

How are particles accelerated to extreme energies producing shocks, jets and cosmic rays?

Key Performance Requirements

Mirror Effective Area	3 m^2 @1.25 keV 0.65 m^2 @ 6 keV 150 cm^2 @ 30 keV	Black hole evolution, large scale structure, cosmic feedback, EOS Strong gravity, EOS Cosmic acceleration, strong gravity
Spectral Resolution/FOV E = 0.3 – 7 keV E = 0.3 –1 keV	ΔE = 2.5 eV within 2 arc min 10 eV within 5 arc min < 150 eV within 18 arc min E/ΔE = 3000 from with an area of 1,000 cm^2	Black Hole evolution, Large scale structure Missing baryons using tens of AGN
Mirror Angular Resolution	≤5 arc sec HPD <7 keV ≤30 arc sec HPD > 7 keV	Large scale structure, cosmic feedback, black hole evolution, missing baryons Black hole evolution
Count Rate	1 Crab with >90% throughput	Strong gravity, EOS
Polarimetry	1% MDP on 1 mCrab in 100 ksec (2 - 6 keV)	AGN geometry, strong gravity
Astrometry	1 arcsec at 3 σ confidence	Black hole evolution
Absolute Timing	50 μ sec	Neutron star studies

How do Supermassive Black Holes Grow and Evolve?



20 day exposure with Chandra will be a routine observation for IXO

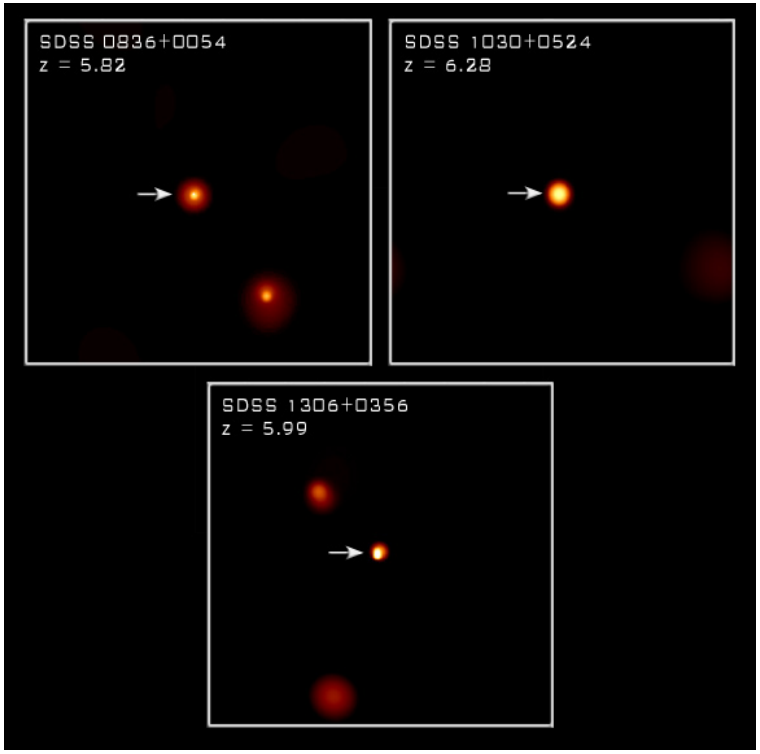
Chandra and XMM-Newton deep fields reveal that super-massive Black Holes are common throughout the Universe and that X-ray observations are a powerful tracer of their evolution

Most of these sources have <30 detected X-ray counts even in 20-day ultradeep X-ray surveys

IXO will greatly expand our view of the accretion light of the high-redshift Universe

IXO will bring a factor of 10 gain in telescope aperture combined with next generation instrument technology to realize a quantum leap in capability

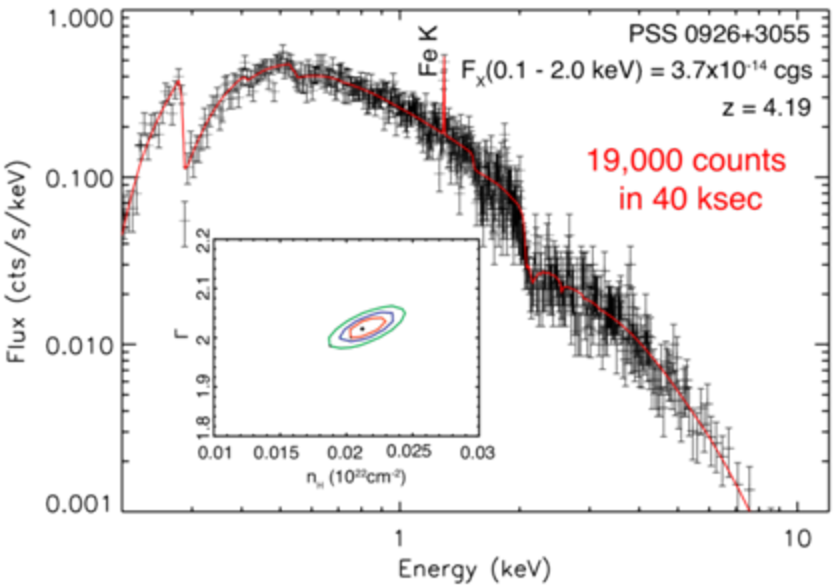
How do AGN evolve at high redshift?



Chandra has detected X-ray emission from ~100 quasars at z > 4

Flux is beyond grasp of XMM-Newton and Chandra high resolution spectrometers, but well within the capabilities of IXO

IXO Simulation (40 ks)



X-ray spectra can give:

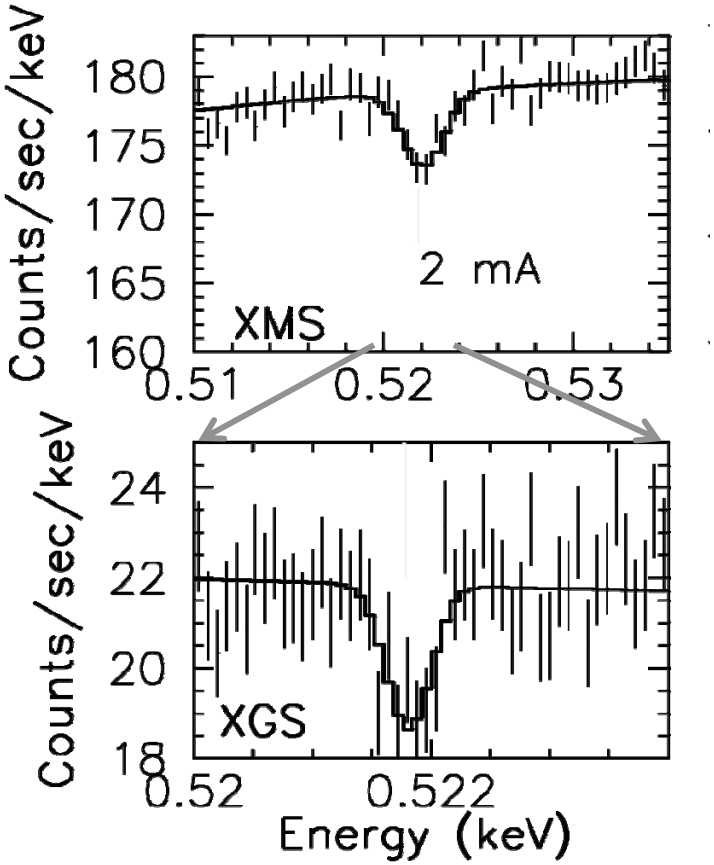
redshifts!

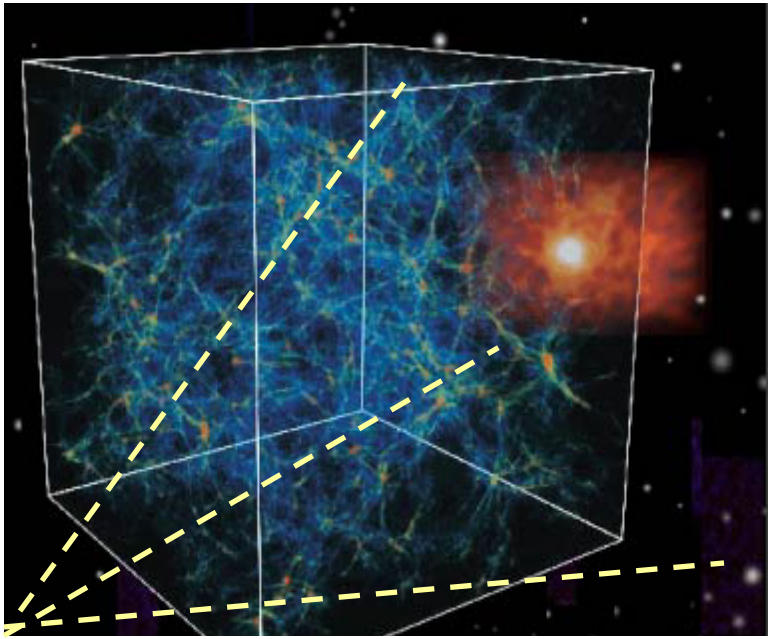
disk ionization

constraint of L/L_{Edd}

Are the missing baryons in the local Universe in the Cosmic Web and if so, how were they heated and infused with metals?

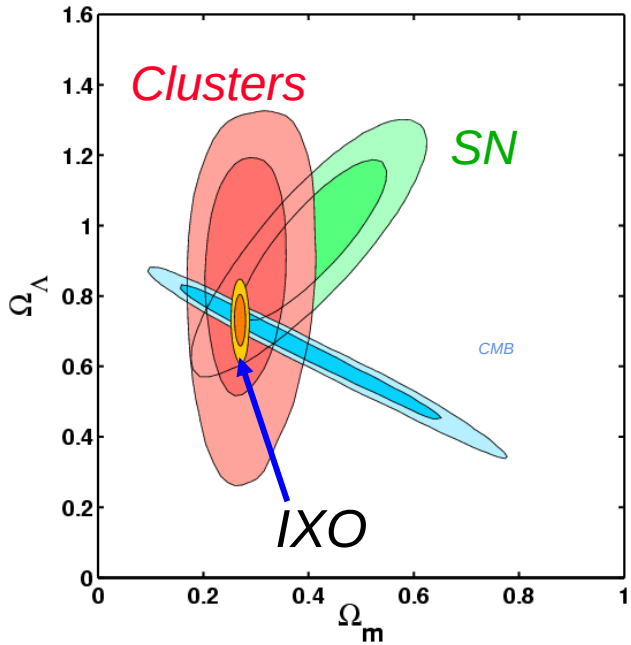
40% of the Baryons in the local Universe are predicted to be caught in a hot plasma trapped in the warm-hot intergalactic medium (WHIM)





IXO will detect ionized gas in the hot IGM medium via OVII absorption lines in spectra of many background AGN to detect the missing Baryons and characterize them

How do relaxed clusters constrain Dark Energy?



IXO gives a factor of ten improvement

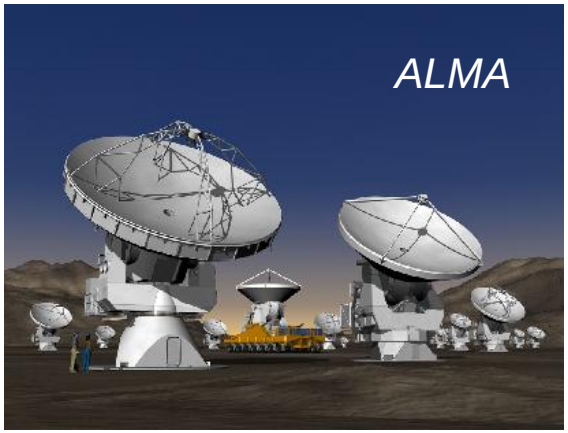
In the terms of the Dark Energy Task Force Figure of Merit this is a Stage IV result

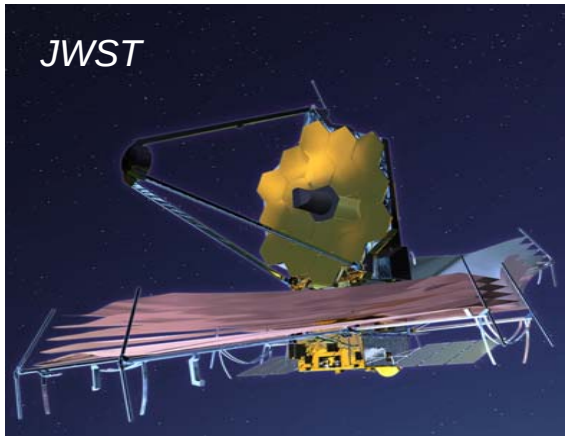
Rapetti, Allen et al 2006 (Astro-ph/0608009)

- *Using the gas mass fraction as a standard ruler measures f_{gas} to 5% (or better) for each of 500 galaxy clusters to give Ω_M=0.300±0.007, Ω_Λ=0.700±0.047*
- *Cluster X-ray properties combined with sub-mm data measure absolute cluster distances via the S-Z effect and cross-check f_{gas} results with similar accuracy*
- *Determining the evolution of the cluster mass function with redshift reveals the growth of structure and provides a powerful independent check*

IXO: A future astrophysics great observatory

Sub-mm





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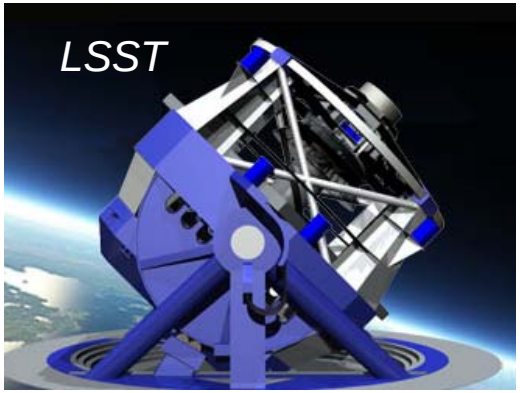
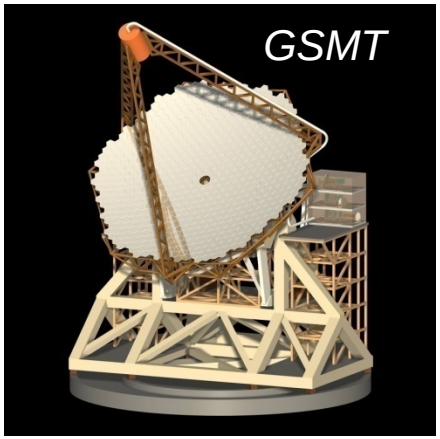
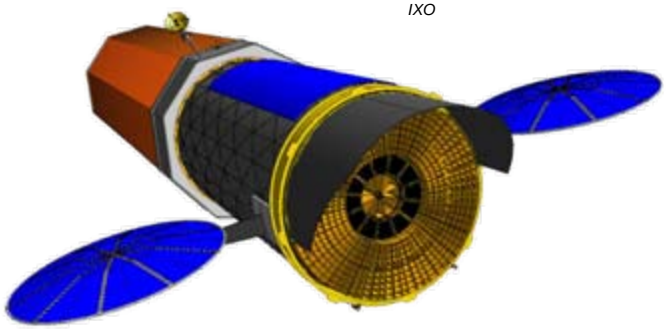




Optical

IXO



X-ray

The two order of magnitude increase in capability of IXO is well matched to that of other large facilities planned for the next decade

Q18

Mission Payload

Flight Mirror Assembly (FMA)

- ***Highly nested grazing incidence optics***

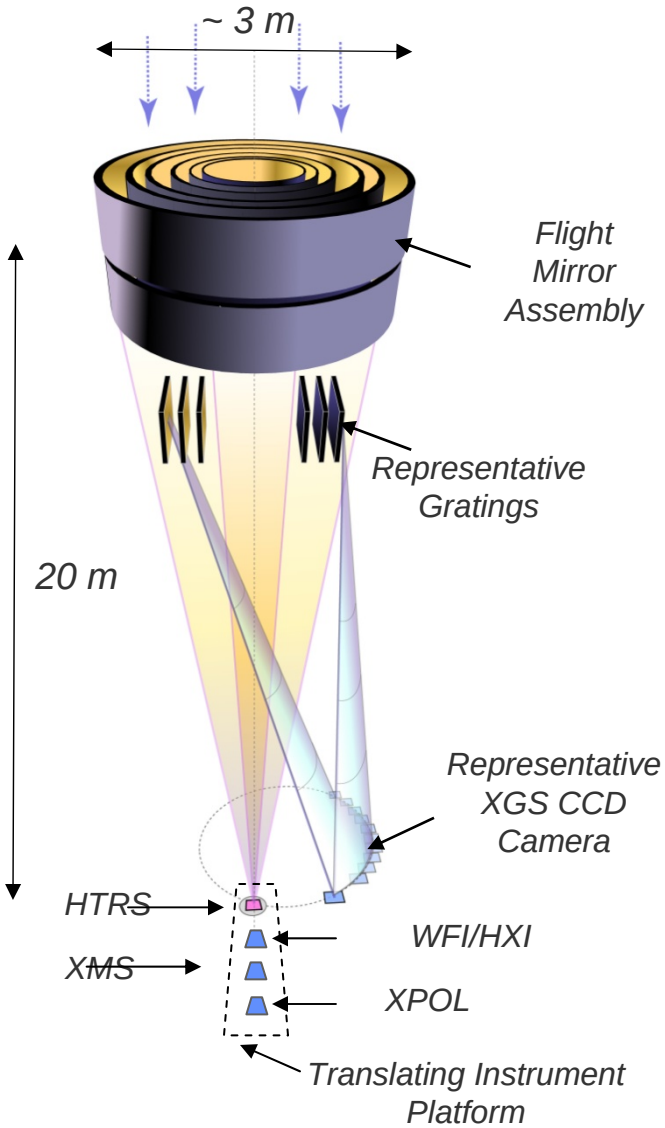
Spectroscopy Instruments

- ***X-ray Micro-calorimeter Spectrometer (XMS)***
- ***X-ray Grating Spectrometer (XGS)***

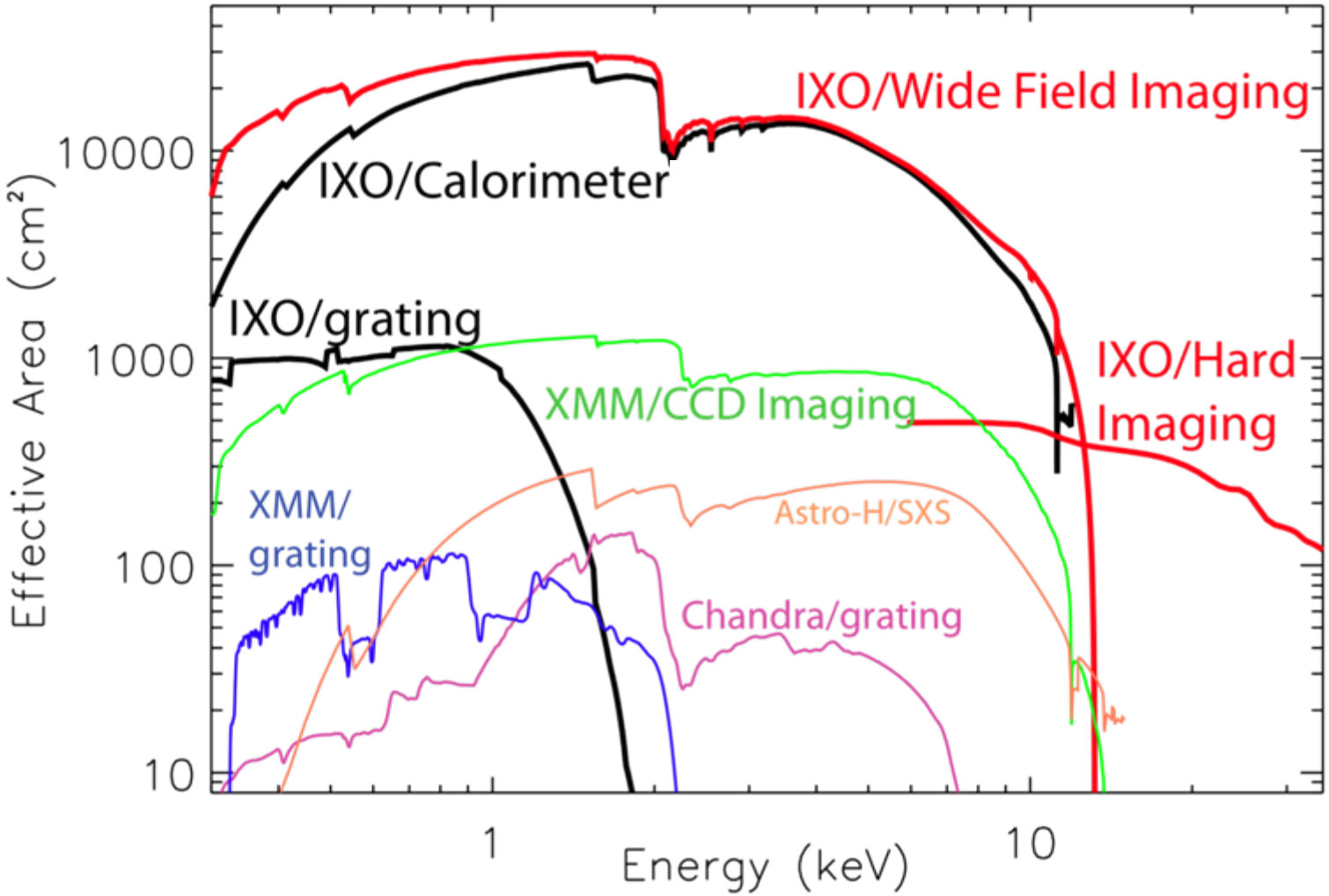
Imaging, Timing and Polarimetry Instruments

- ***Wide Field Imager (WFI) and Hard X-ray Imager (HXI)***
- ***X-ray Polarimeter (XPOL)***
- ***High Time Resolution Spectrometer (HTRS)***

XMS, WFI/HXI, XPOL and HTRS observe one at a time by being inserted into focal plane via a Translating Instrument Platform

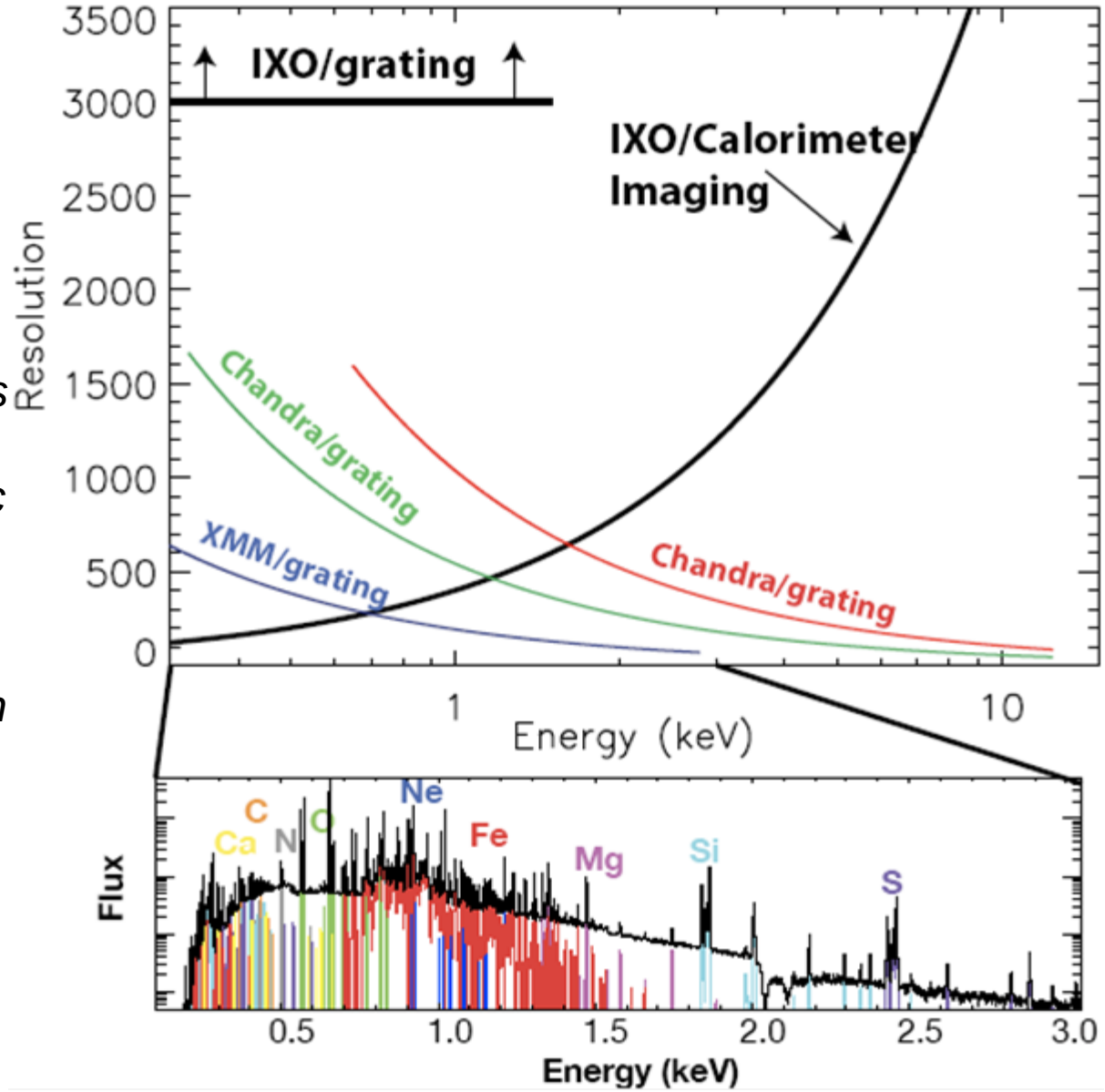


Effective area comparison



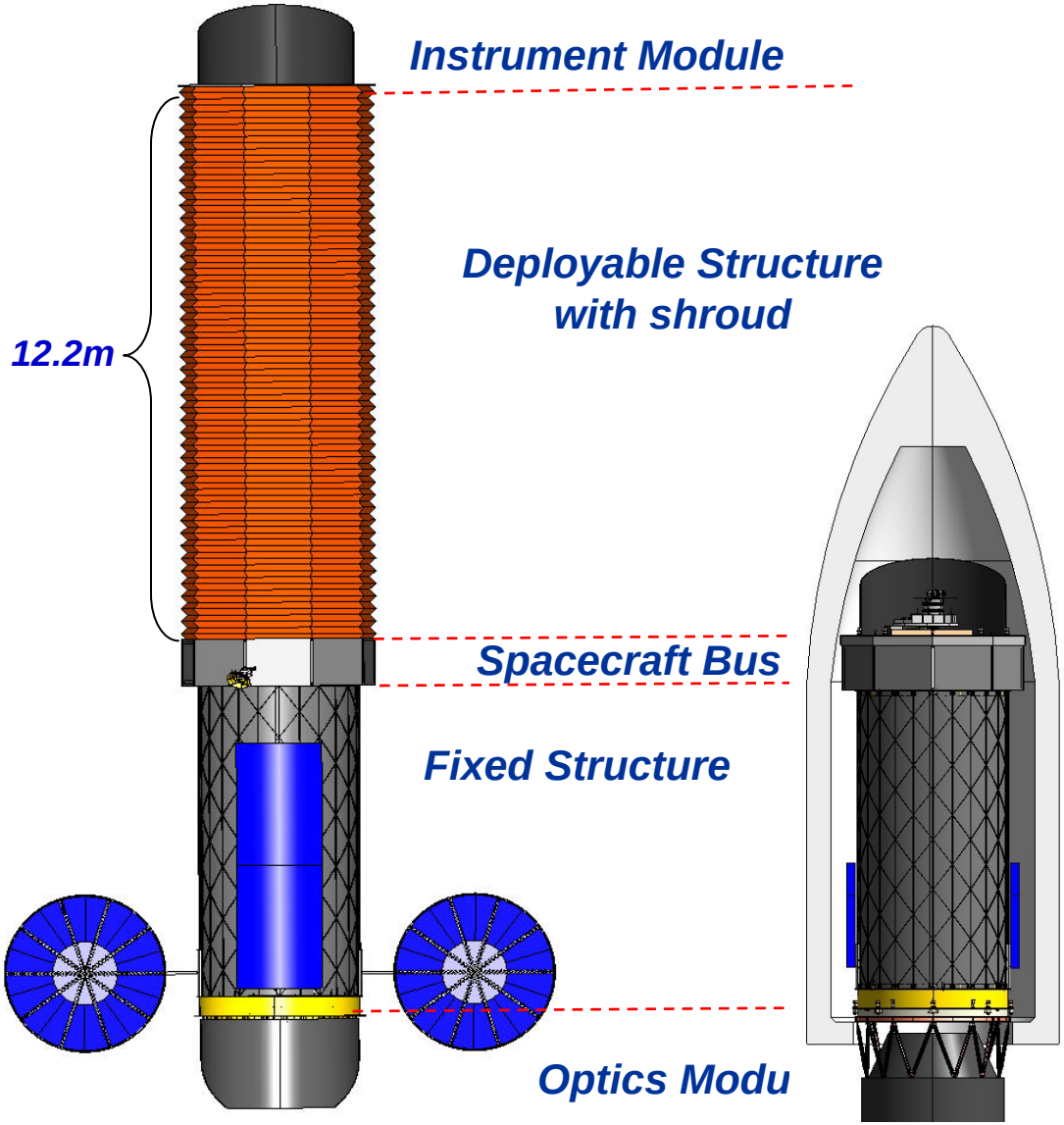
Spectral Capability

The IXO energy band contains the K-line transitions of 25 elements Carbon through Zinc allowing simultaneous direct abundance determinations using line-to-continuum ratios, plasma diagnostics and at iron K bulk velocities of 200 km/s



NASA Mission Design

- *The observatory is deployed to achieve 20 m focal length*
- *Observatory Mass ~6100 kg (including 30% contingency)*
- *Launch on an Atlas V 551 or Ariane V*
- *Direct launch into an 800,000 km semi-major axis L2 orbit*
- *5 year required lifetime, with expendables for 10 year goal*

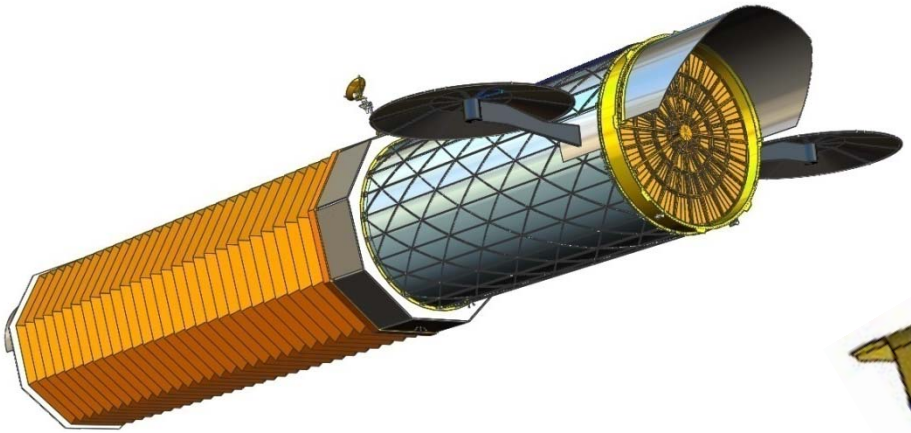


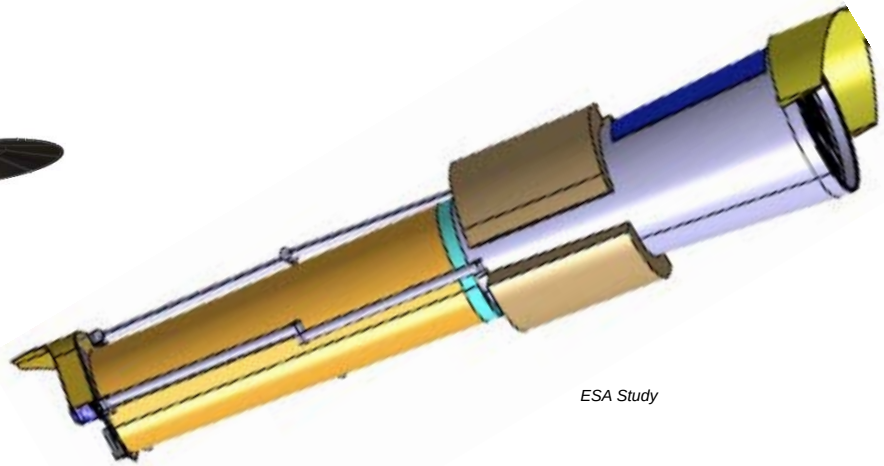
Deployed IXO Configuration

Stowed IXO Configuration

IXO Mission Studies

NASA Study

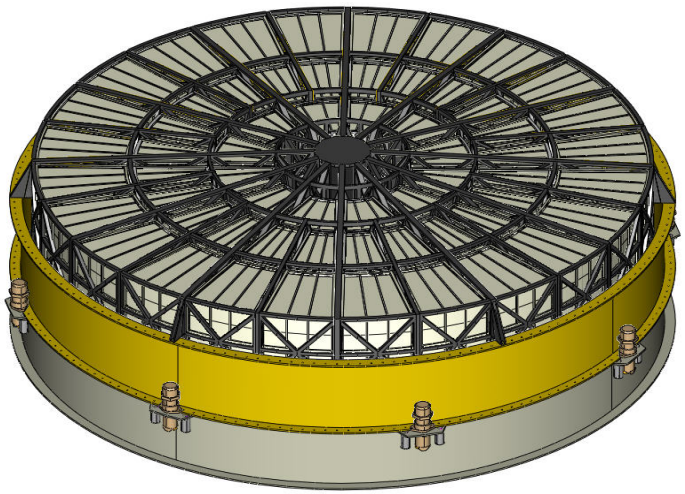




ESA Study

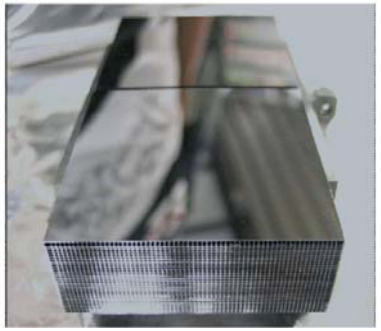
Separate ESA and NASA mission studies demonstrate overall mission feasibility, with no show stoppers

IXO X-ray Telescope



Glass

Silicon



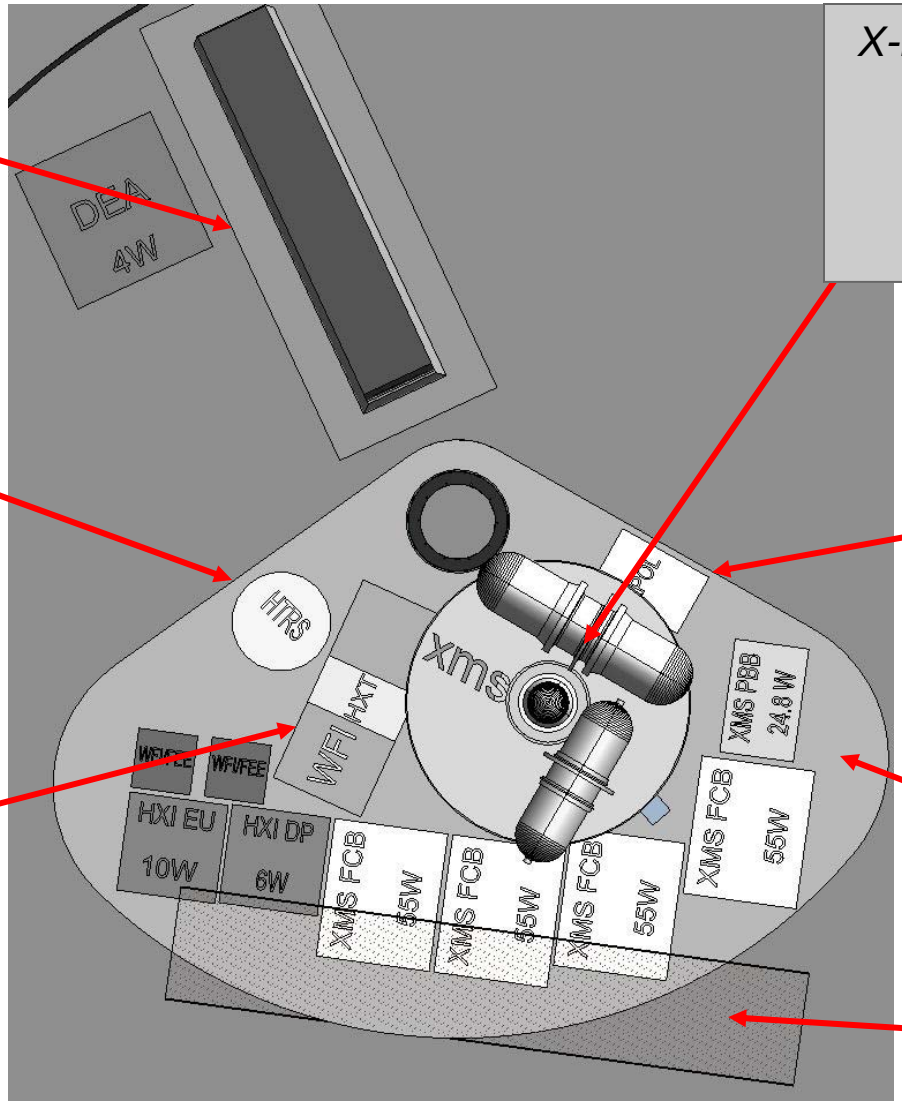
- *Key requirements:*
  - *Effective area ~3 m2 @ 1.25 keV*
  - *Angular Resolution <= 5 arc sec*
- *Single segmented optic with design optimized to minimize mass and maximize collecting area*
  - *Multilayers enhance hard X-ray response to 40 keV*
- *Two parallel technology approaches being pursued*
  - *ESA: Silicon micro-pore optics 3.8m diameter*
  - *NASA: Slumped glass 3.0m diameter*
- *Both making excellent progress*
  - *Already achieved 15 arc sec resolution, with further progress planned for this year*
  - *Slumped glass baselined for NuSTAR*

Focal Plane Layout

X-ray Grating Spectrometer Detector
0.3 to 1 keV
R = 3000
> 1000 cm²

High Time Resolution Spectrometer
1 Crab > 90% livetime

Wide Field Imager
FOV 18 arc min
0.1-15 keV
DE < 150 eV
+
Hard X-ray Imager
FOV 8 arc min
> 150 cm²@30 keV



X-ray Micro-calorimeter Spectrometer
FOV 5 arc min
DE = 2.5 eV
0.3-7 keV

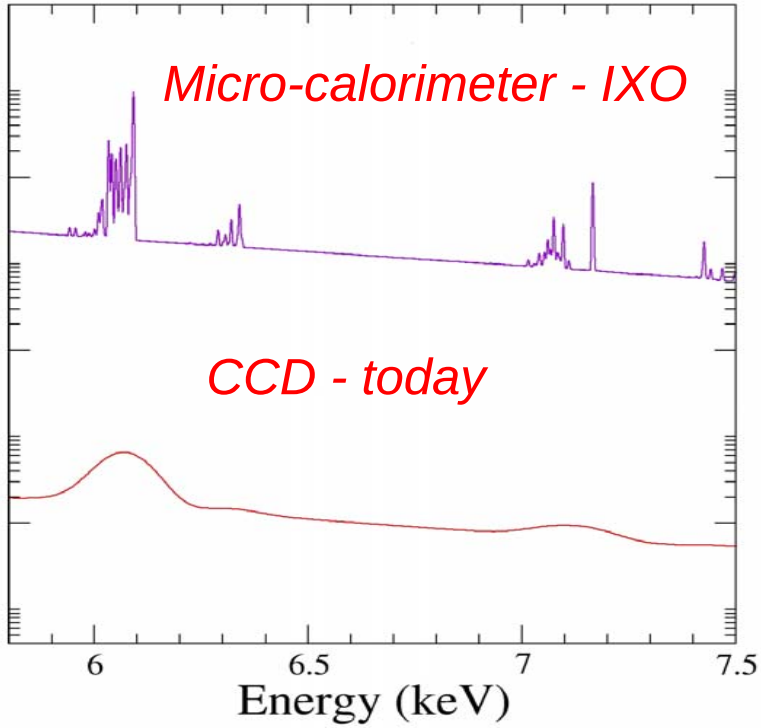
Polarimeter
<1% for 1 mCrab in 100ks

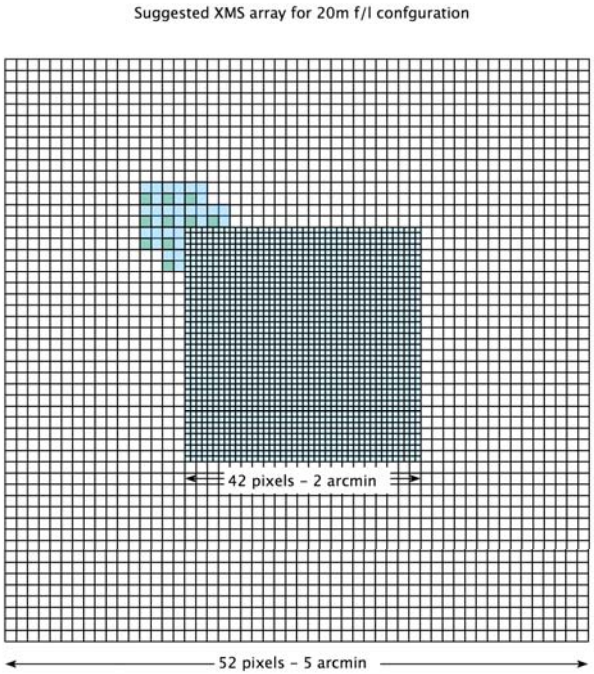
Translation Platform

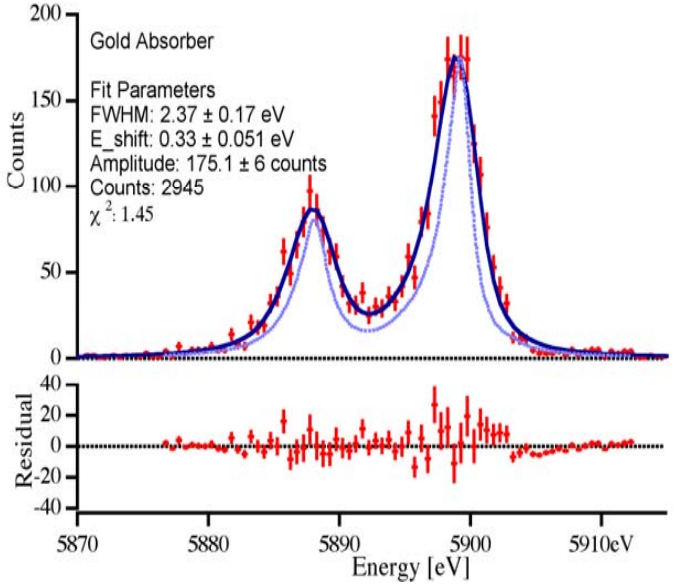
Radiator

Example of Next Generation Instrument Capability X-ray Micro-calorimeter Spectrometer (XMS)

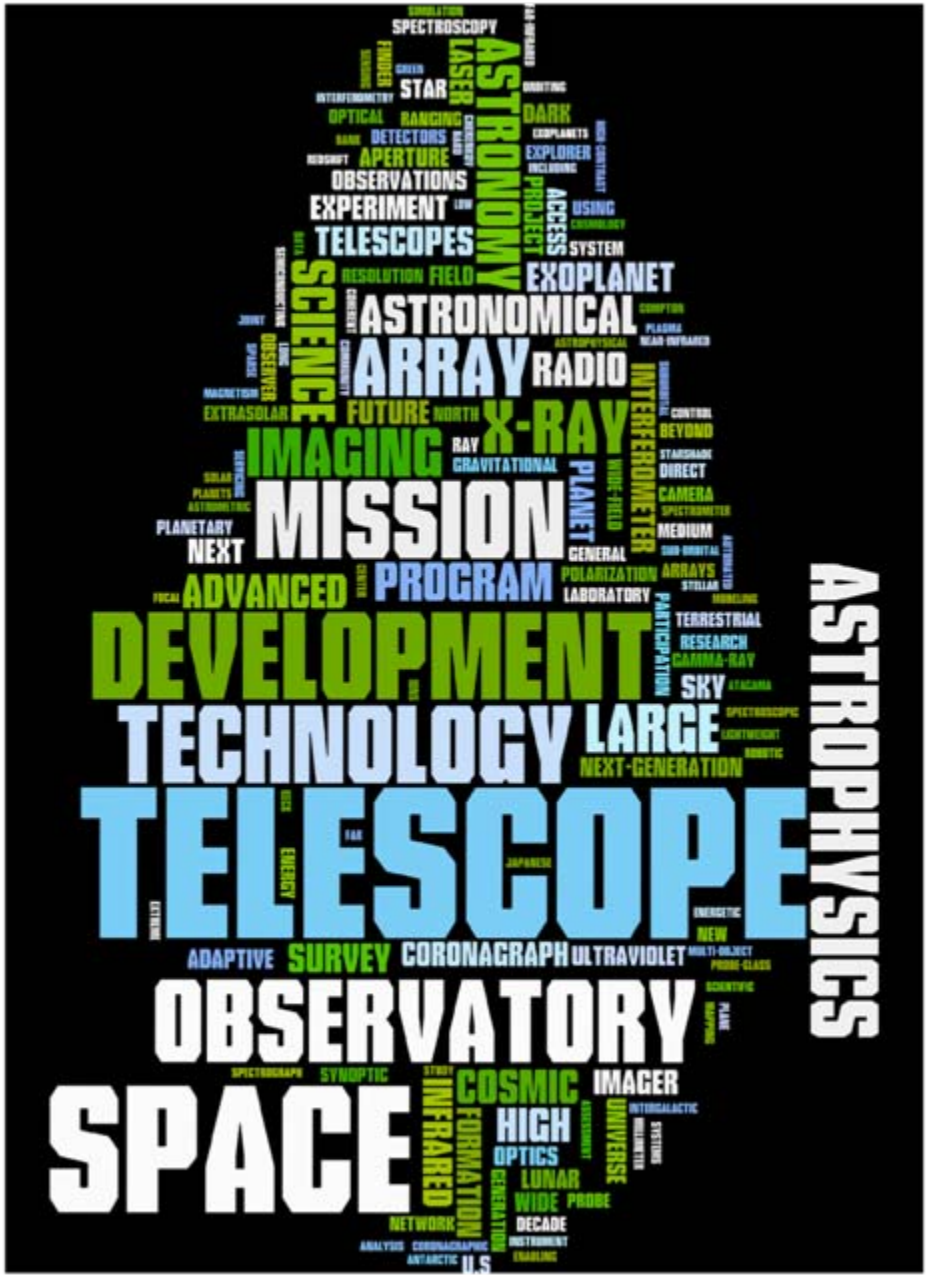
- *Thermal detection of individual X-ray photons*
  - *High spectral resolution*
  - *ΔE very nearly constant with E*
  - *High intrinsic quantum efficiency*
  - *Imaging detectors*







Decadal:
171 NOIs



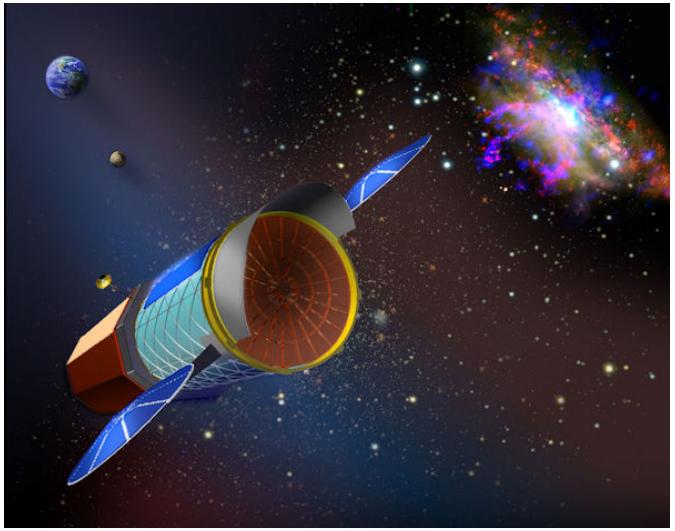
Summary

- ***IXO addresses key and timely questions confronting Astronomy and Astrophysics***
- ***IXO will bring a factor of ten gain in telescope aperture combined with next generation instrument technology to realize a quantum leap in capability***
- ***Separate studies by ESA and NASA demonstrate that the mission implementation for a 2020 launch is feasible with no major show stoppers***

IXO Table Top Review

2009 03 12, NASA GSFC

Mission Overview



Gabe Karpati

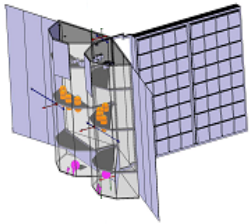
IXO Mission Systems Engineer

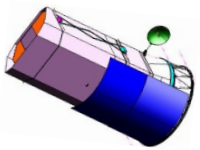
Previous ("Constellation-X") Configurations

2002

Two ATLAS V 551

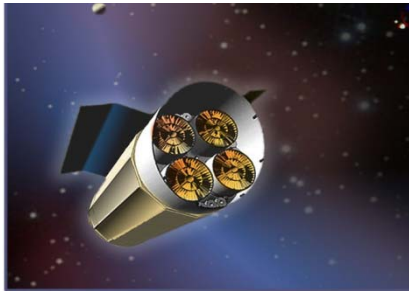
2004



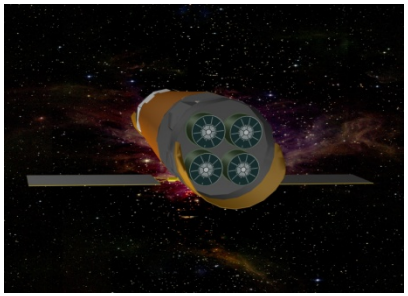


Delta IV H

2005



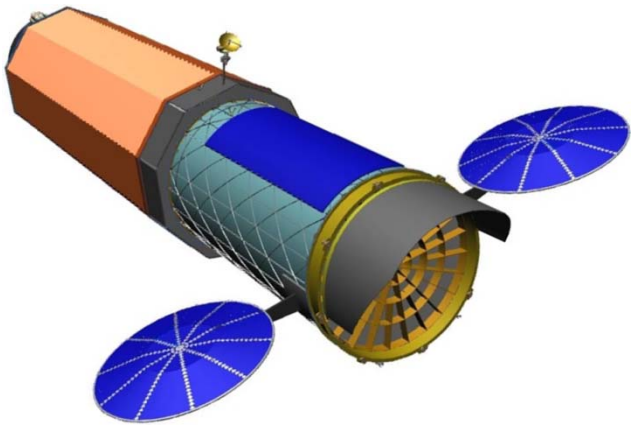
2007

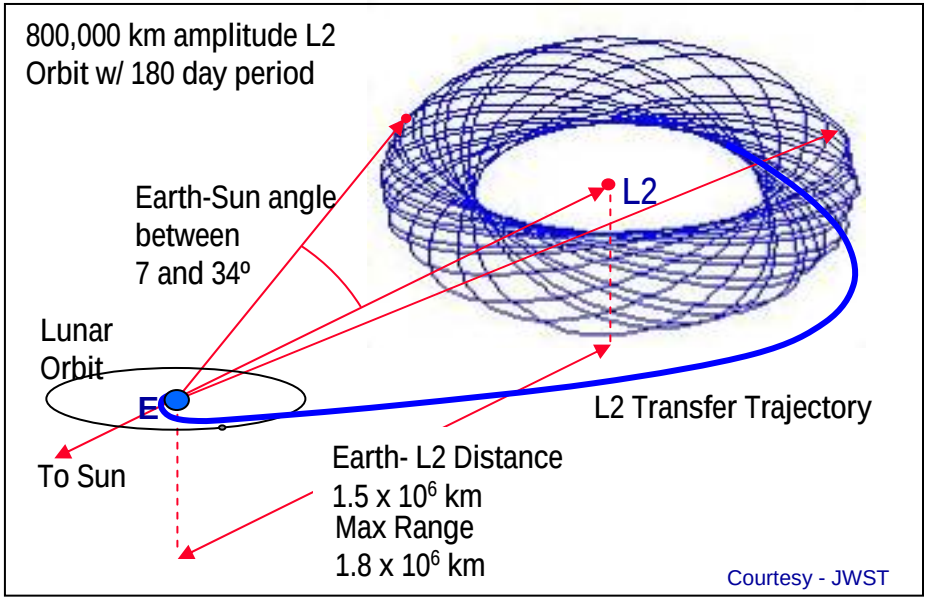


Single ATLAS V 551

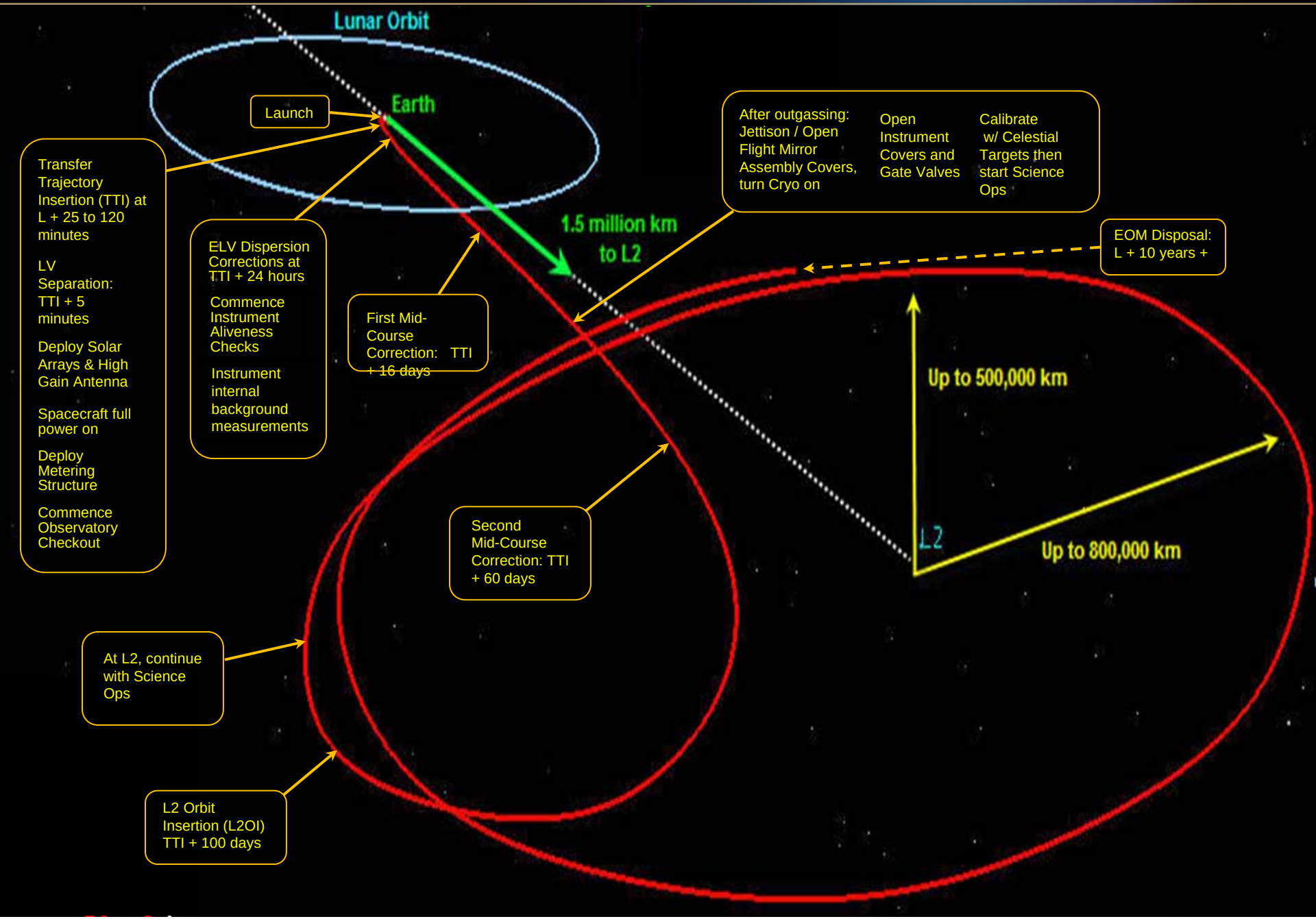
IXO Mission

- International Collaboration
  - NASA, ESA, JAXA
- Payload
  - 3.2 m dia X-ray mirror
  - 20 m focal length w/ 12.2mextensible metering structure
  - Five science instruments for imaging and spectroscopy
- Mission Class
  - Mission Life: 5 years required, 10 years goal, consumables sized for 10 years
  - Class B : no performance degradation w/ single point failure
- Launch
  - December 2020
  - Atlas V 551 medium fairing or Ariane 5
  - Max Liftoff Mass: 6425
  - Direct launch into “zero Insertion delta-v” L2 orbit
  - 100 day cruise
- Orbit
  - L2 800,000 km semi-major axis halo orbit
  - 0% solar or lunar obscuration throughout 10 years

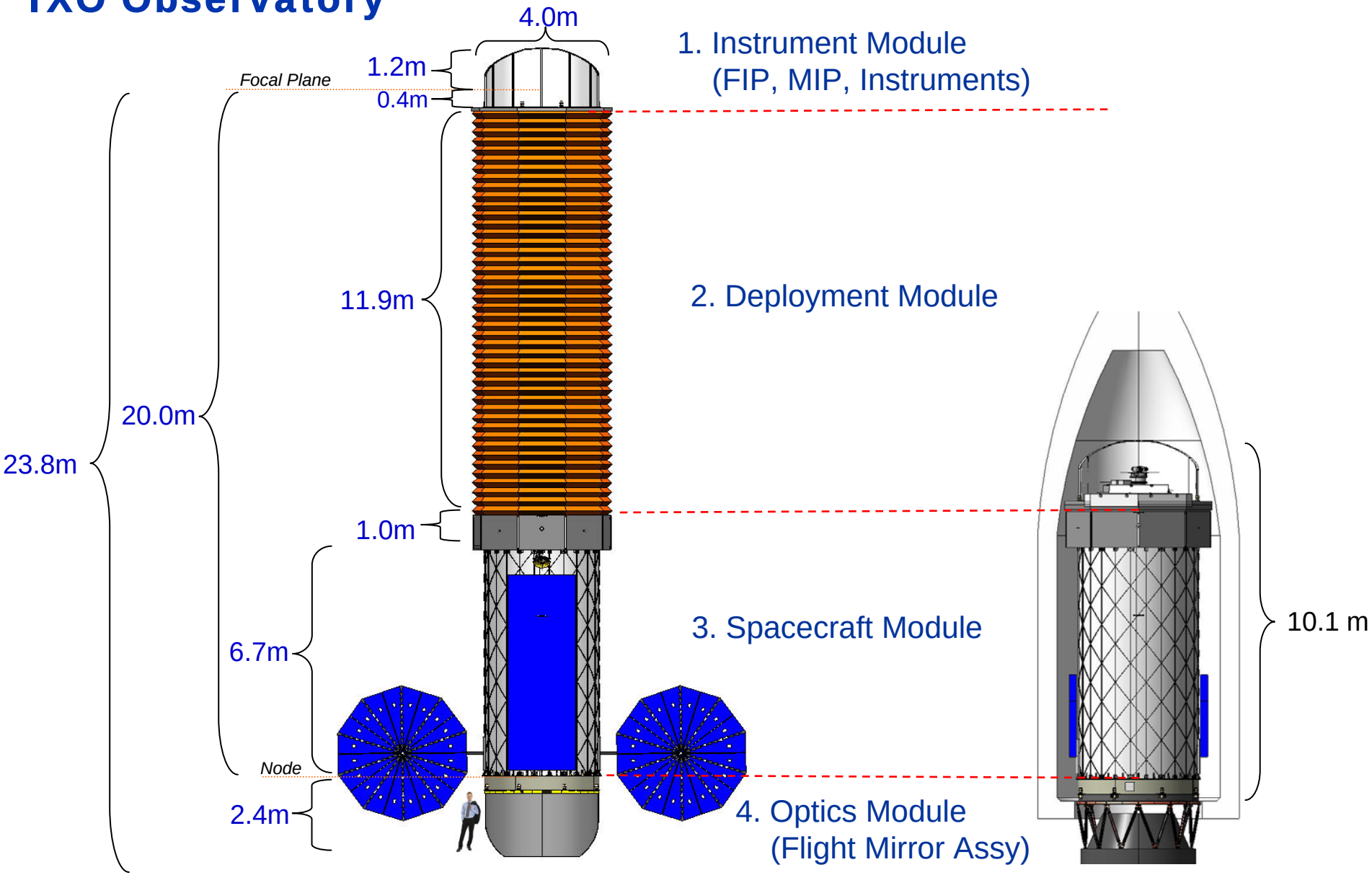




Mission Timeline



IXO Observatory



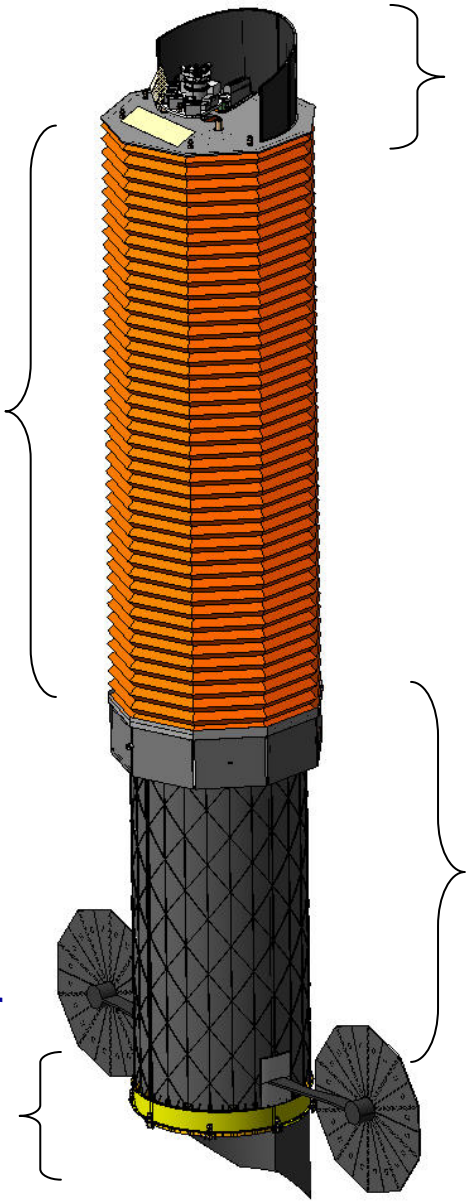
Observatory Modules

Instrument Module

- Fixed Sunshade
- Moveable Instrument Platform (MIP) w/ four Instruments: XMS, WFI/HXI, X-POL, HTRS
- Fixed Instrument Platform (FIP) w/ fifth Instrument: XGS Camera

Deployment Module

- Three extensible ADAM-type masts with harness (not shown)
- 3.9 m diameter shroud, Whipple shield construction for micrometeoroid protection
- Two 3.5 m dia X-ray baffles



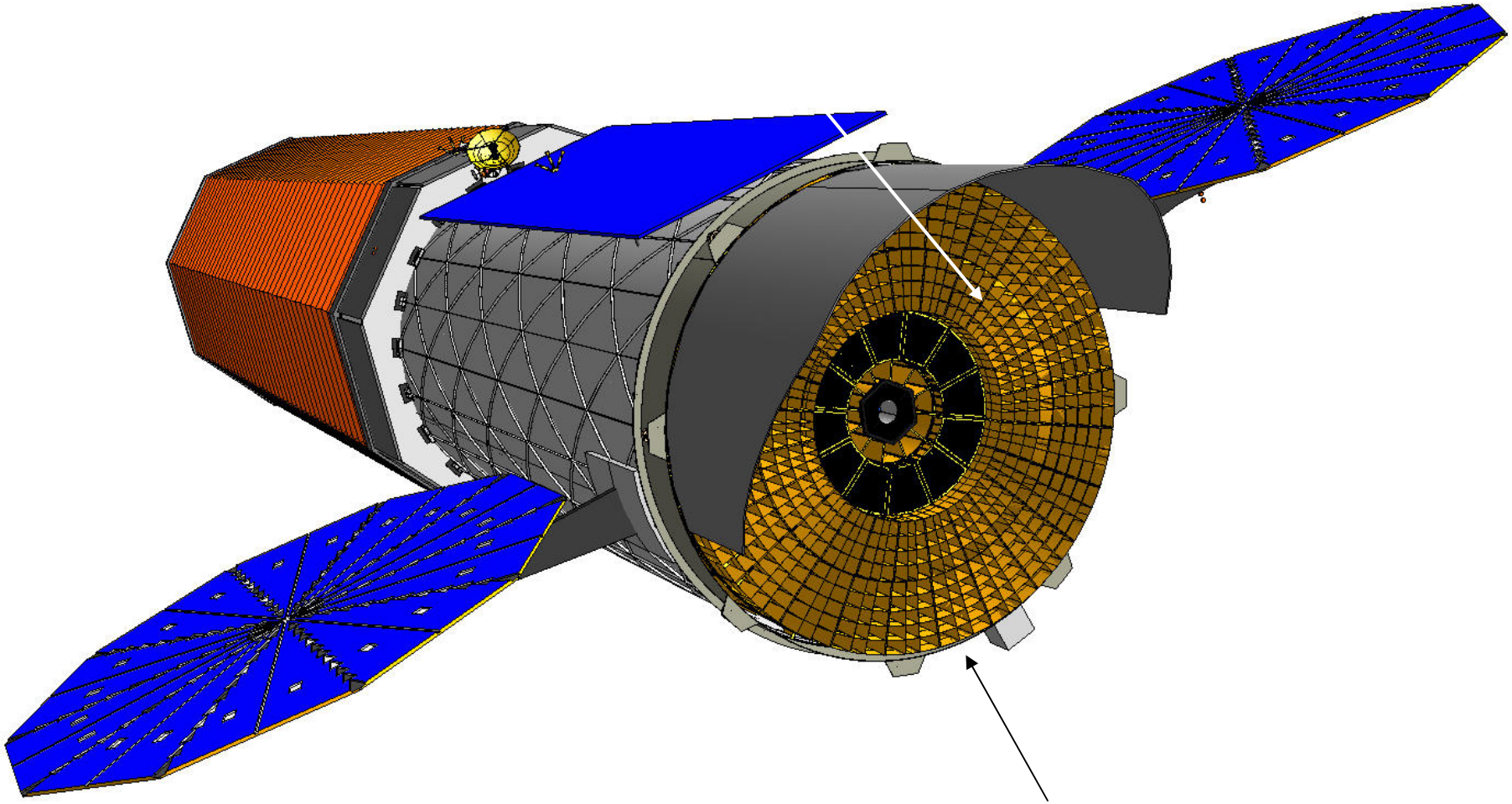
Spacecraft Module

- Nine sided S/C bus structure houses most hardware: avionics, power system electronics, battery, propulsion tanks, reaction wheels, etc.
- Composite isogrid metering structure / thrust tube
- High Gain Antenna
- 25 m2 totqal body mounted and deployable non-articulated 3.4 m dia Ultraflex solar arrays
- Biprop and monoprop thrusters (14)

Optics Module

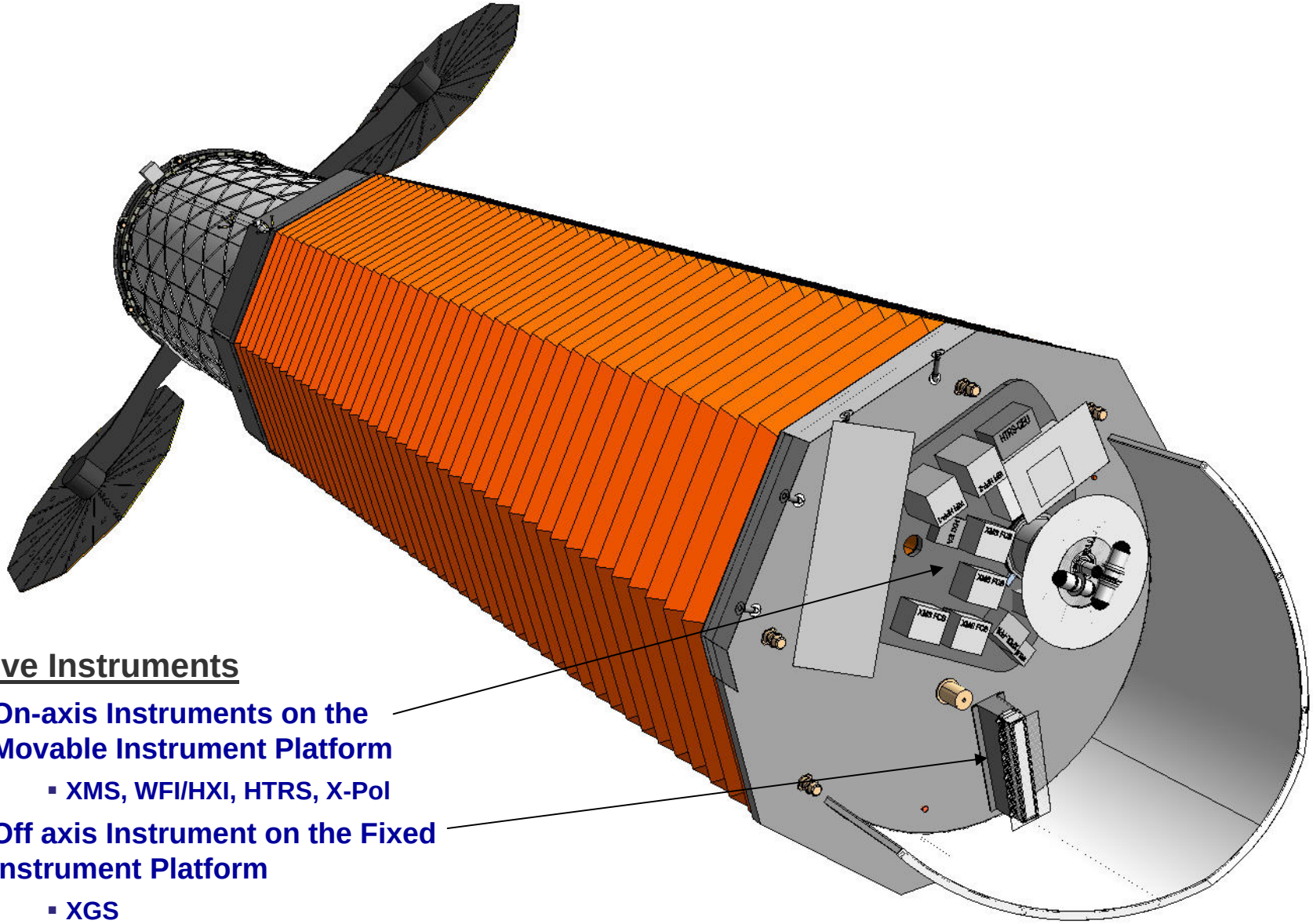
- Flight Mirror Assembly (FMA)
- FMA deployable outer and inner covers
- Deployable Sunshade
- TADS Fore Assy (Periscope)

Observatory Fore View



Flight Mirror Assembly (FMA) with 3.3 m dia Soft X-ray Telescope and .4 m dia Hard X-ray Mirror Module

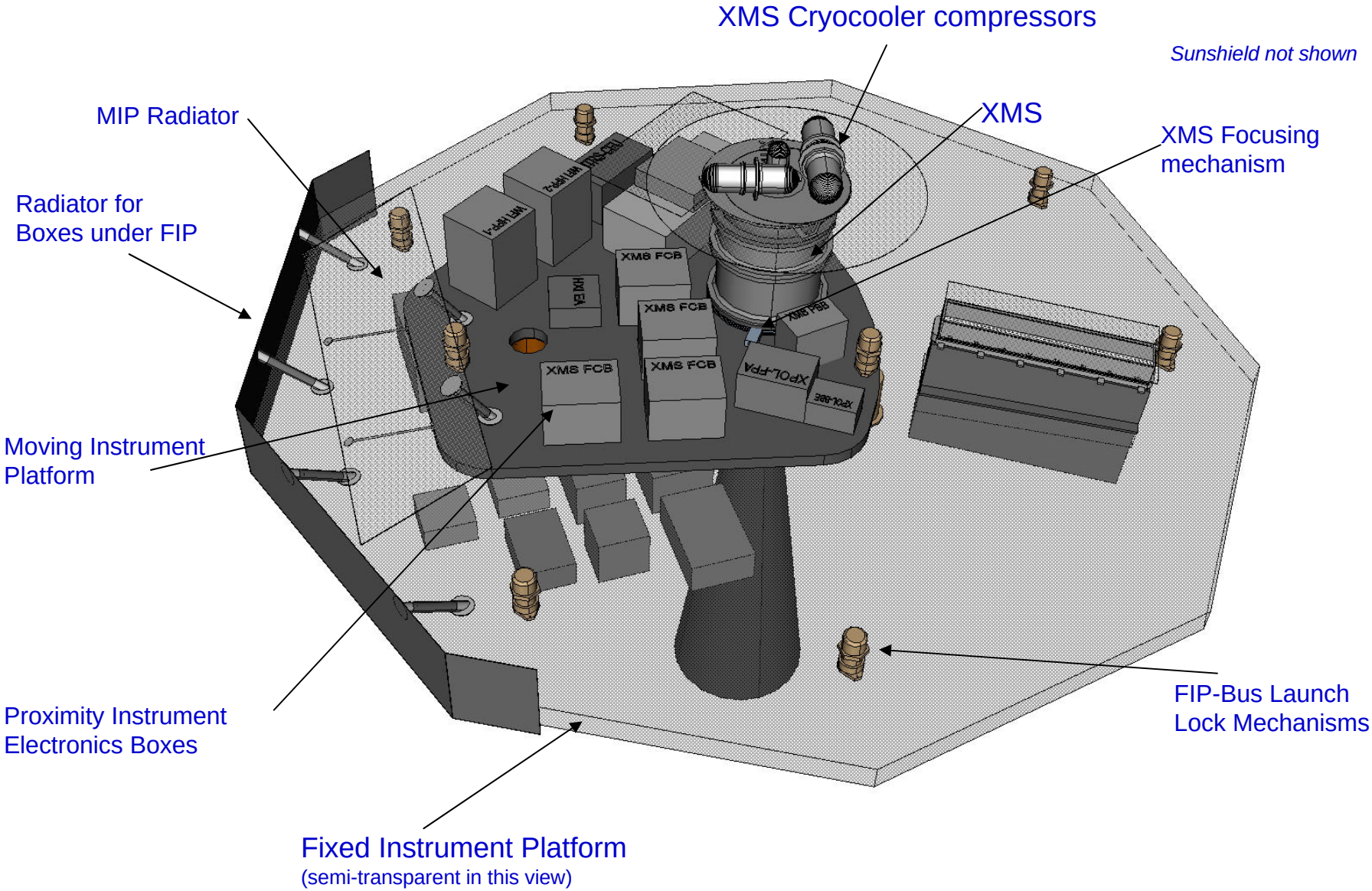
Observatory Aft View



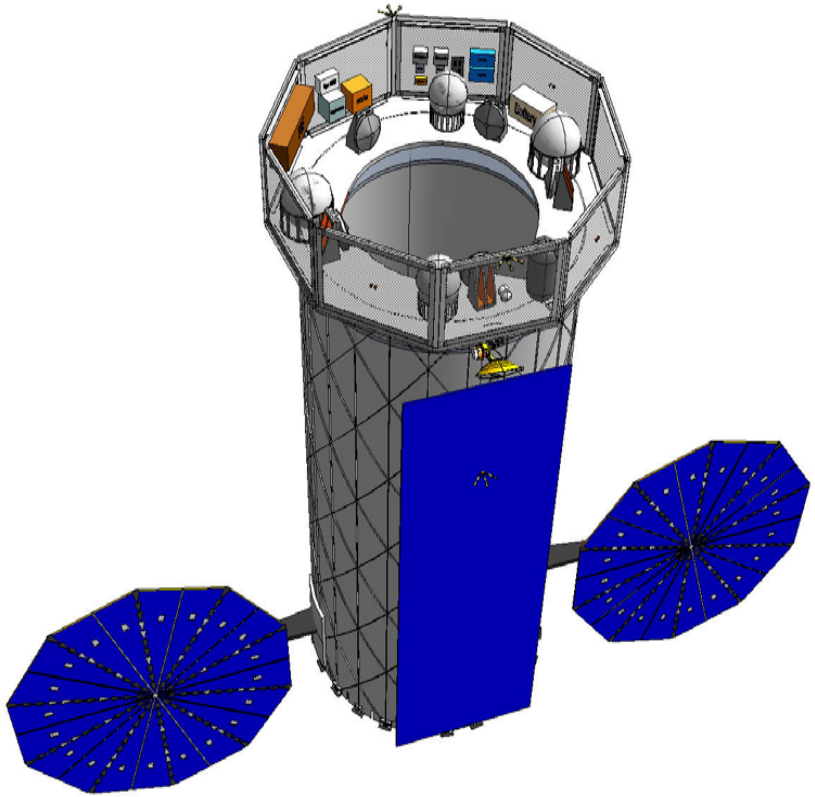
Five Instruments

- **On-axis Instruments on the Movable Instrument Platform**
  - **XMS, WFI/HXI, HTRS, X-Pol**
- **Off axis Instrument on the Fixed Instrument Platform**
  - **XGS**

Instrument Module See Thru View

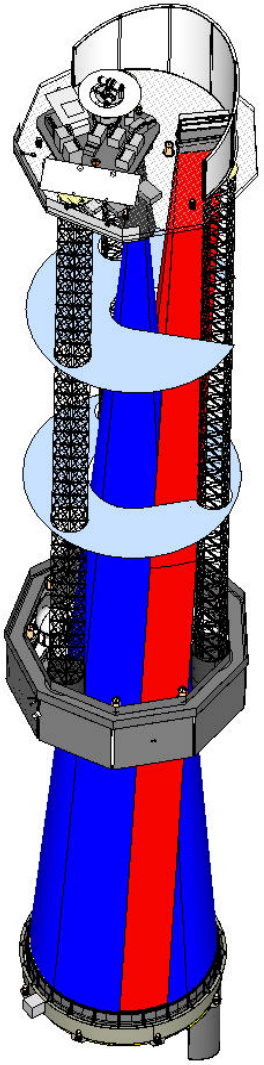


Spacecraft Module and Metering Structure

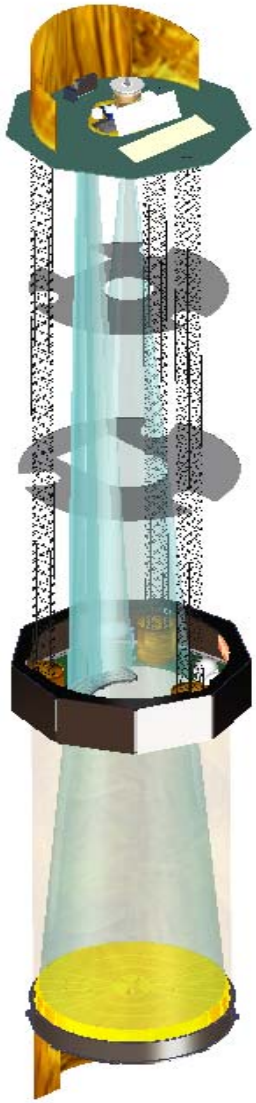


X-ray Beams and Baffles

- The X-ray traces of the FMA and XGS traverse nearly the entire length of the observatory
- Either Critical Angle Transmission Gratings (CATG) or Off-Plane Gratings (OP) XGS can be accommodated
- The x-ray beams drive the size, shape and placement of the spacecraft bus "ring"
  - Needs to be forward of the FMA for sufficient volume for bus components
  - Distance between the bus and the FMA limited to fit in the Atlas V 5 medium fairing
  - (CG, mass propellant lines are additional considerations)



CATG XGS

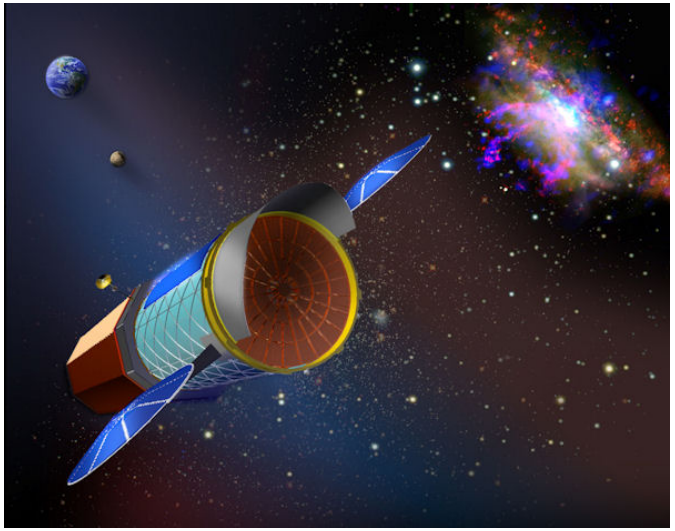


OP XGS

IXO Systems Table Top Review

2009 03 12
NASA GSFC, Bldg 23, Room C130D

Flight Mirror Assembly (FMA) Overview / Requirements



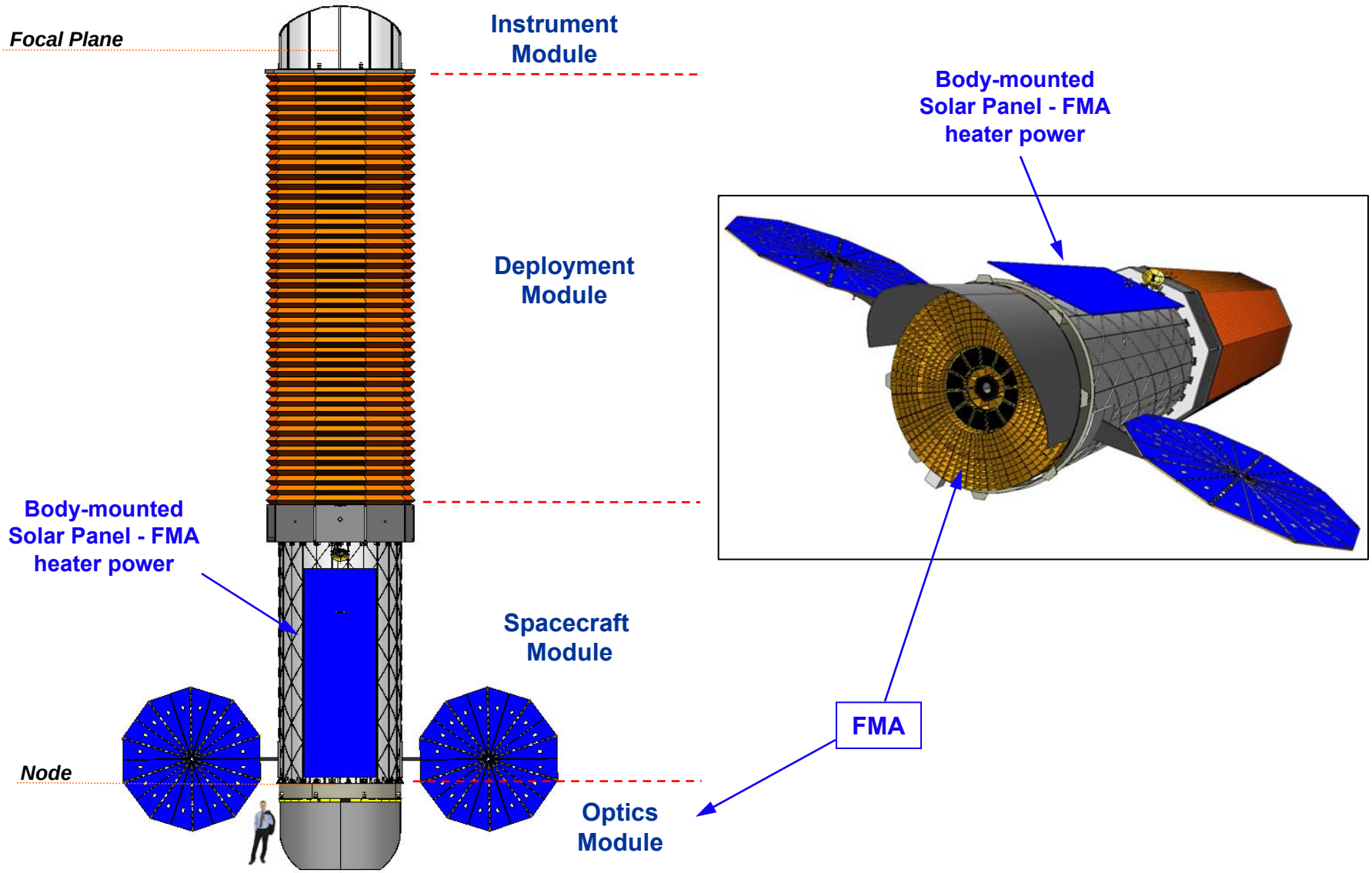
Mike Hill

IXO FMA Systems Engineer

Agenda

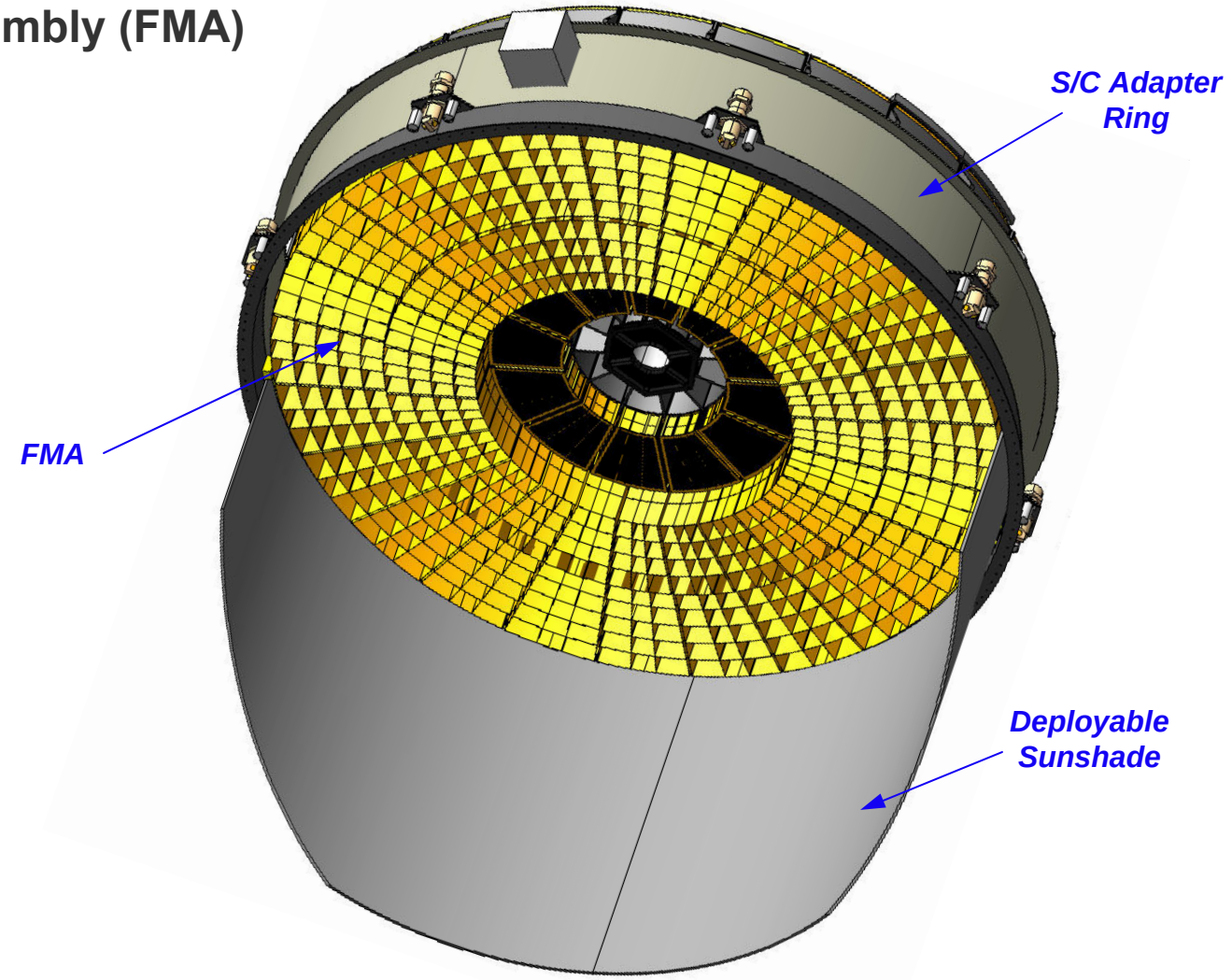
- IXO Observatory Configuration
  - IXO Optics Module Configuration
    - FMA Configuration/Interfaces
      - » FMA Subsystems
        - ~ X-Ray Optic Primer
        - ~ SXT Mirror Development
        - ~ SXT Mirror Module
        - ~ SXT Mirror Bonding Steps
- Traceability of Mission Requirements to FMA Requirements
- FMA System Budgets
- FMA Subsystem Requirements
- FMA Integration and Test Flow

IXO Observatory Configuration



IXO Optics Module Configuration

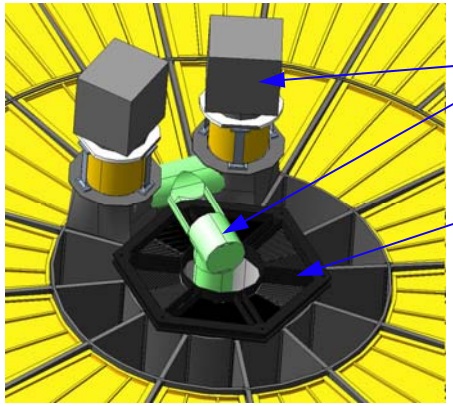
- Flight Mirror Assembly (FMA)
- Sunshade
- S/C Adapter Ring

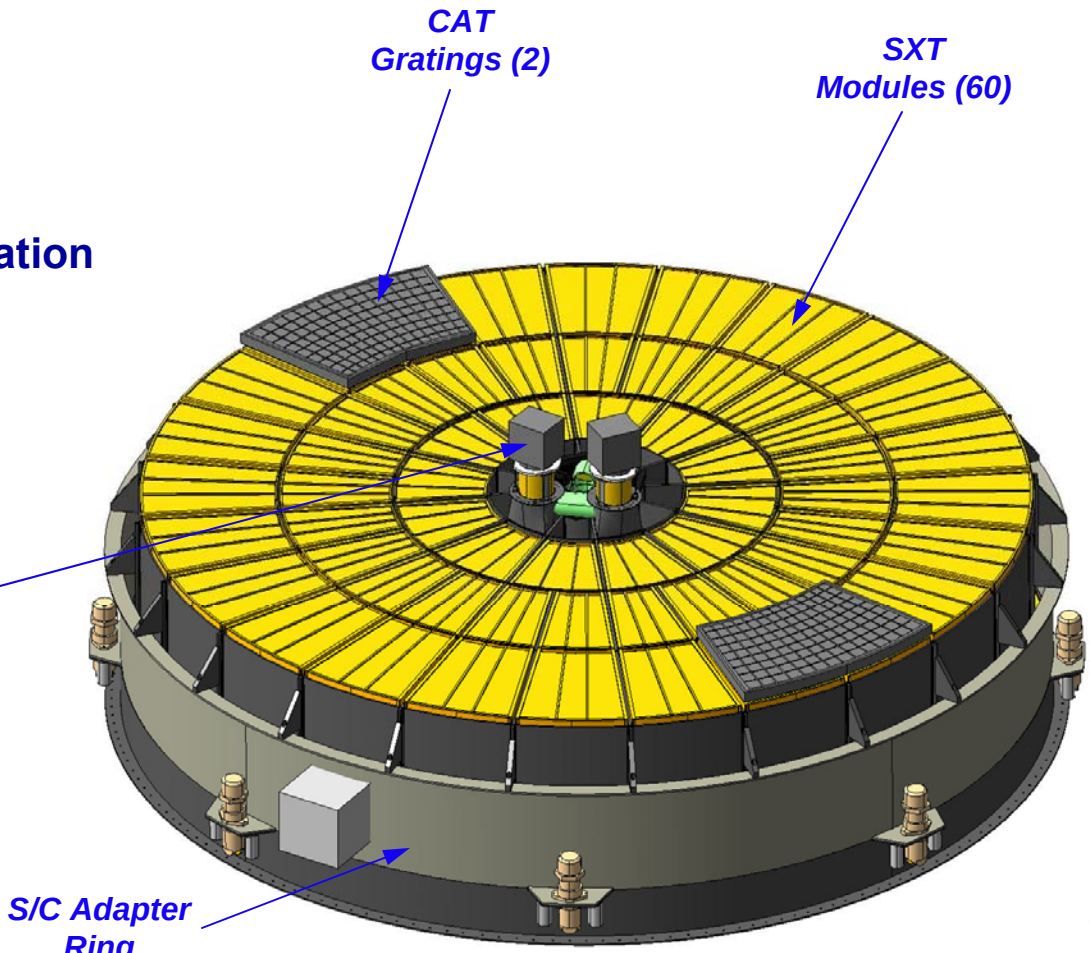


FMA Configuration

- Soft X-Ray Telescope (SXT) Modules
- Hard X-Ray Mirror Module (HXMM)

- Interfaces:
  - S/C Adapter Ring
  - Star Trackers (ST's)
  - Telescope Aspect Determination System (TADS)
  - Critical Angle Transmission (CAT) Gratings (if selected)



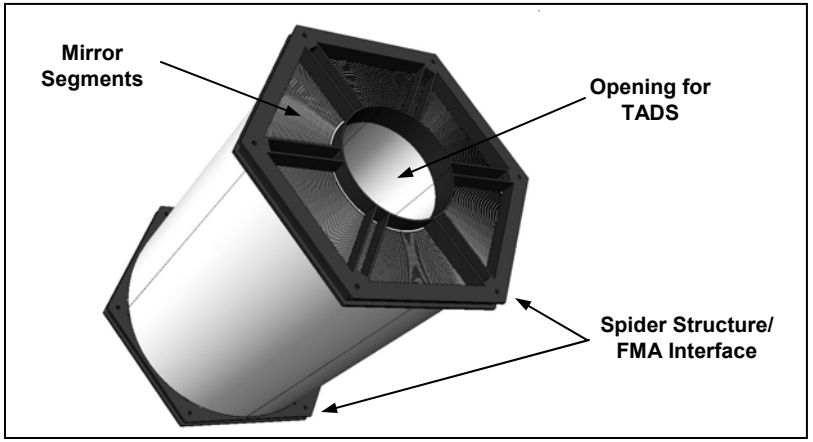


FMA Subsystems

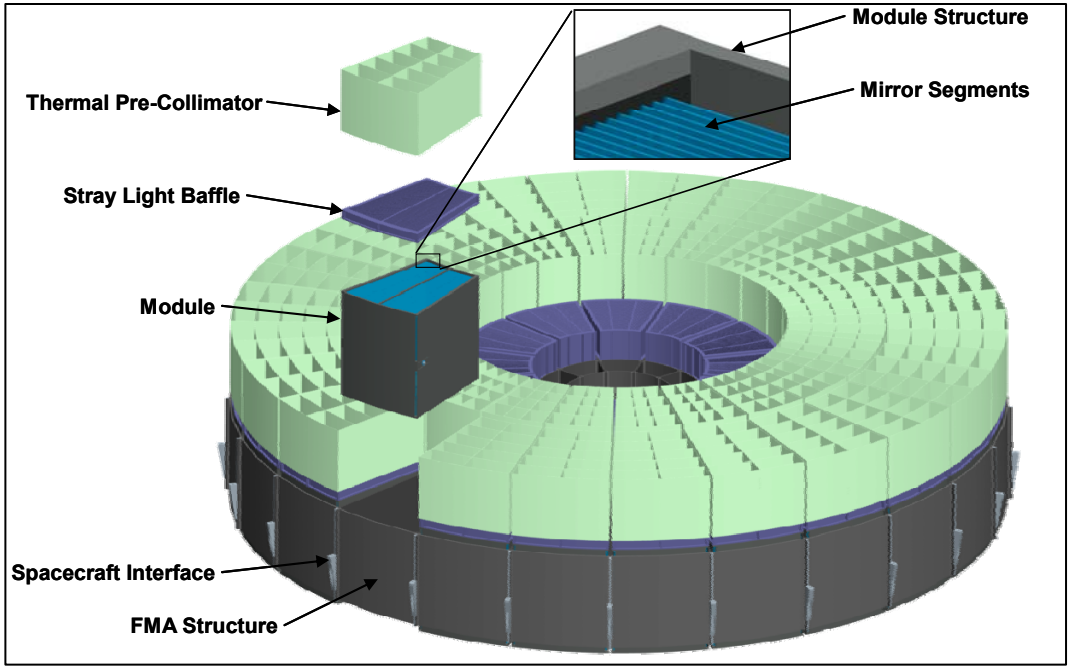
- Optical Subsystem:
  - Soft X-Ray Telescope (SXT)
    - Primary mirror segments
    - Secondary mirror segments
    - Stray Light Baffles *
  - Hard X-Ray Mirror Module (HXMM)
- Mechanical Subsystem:
  - Module structure
  - FMA structure
- Thermal Subsystem:
  - Thermal Pre-Collimators *
  - Thermal Shields
  - Heaters/Harnesses

** Components that have shared Optical/Thermal attributes*

HXMM Configuration

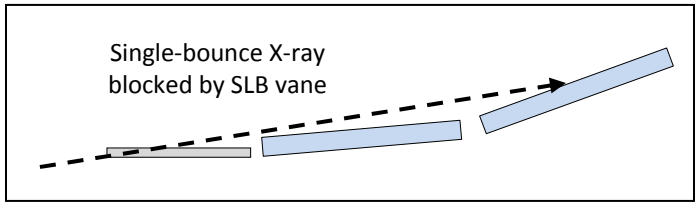


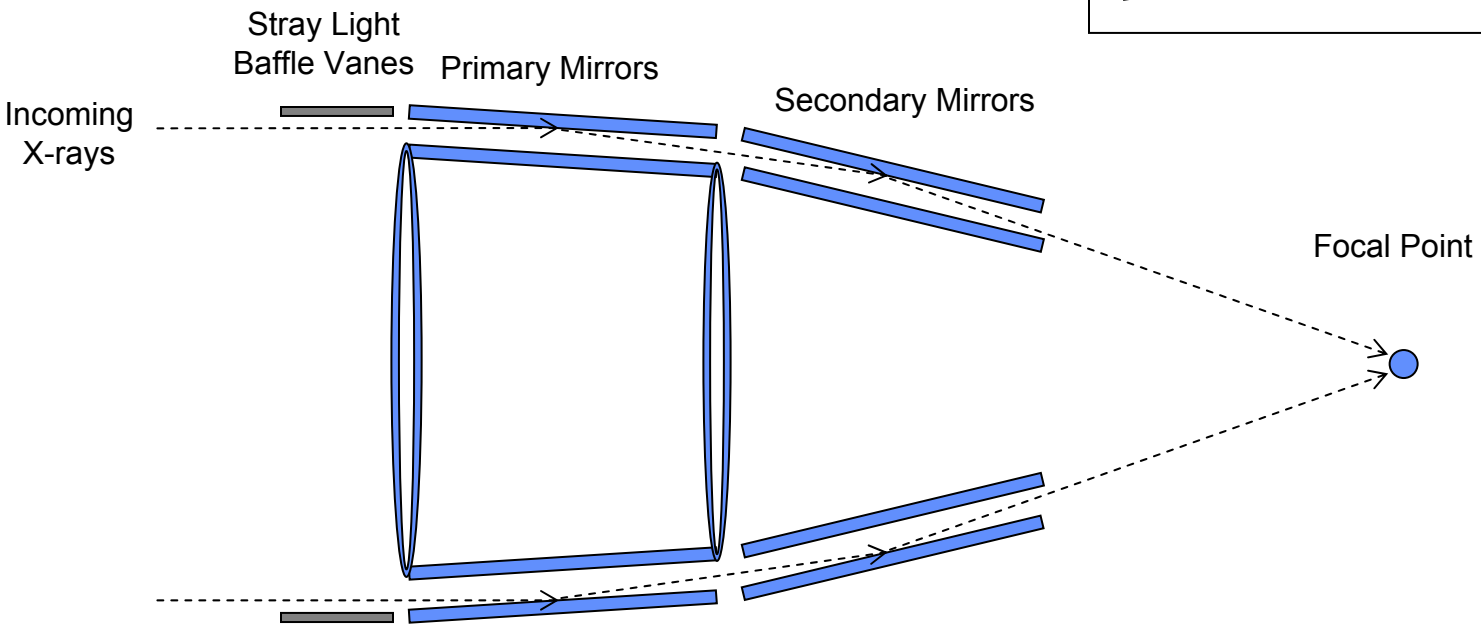
SXT Configuration



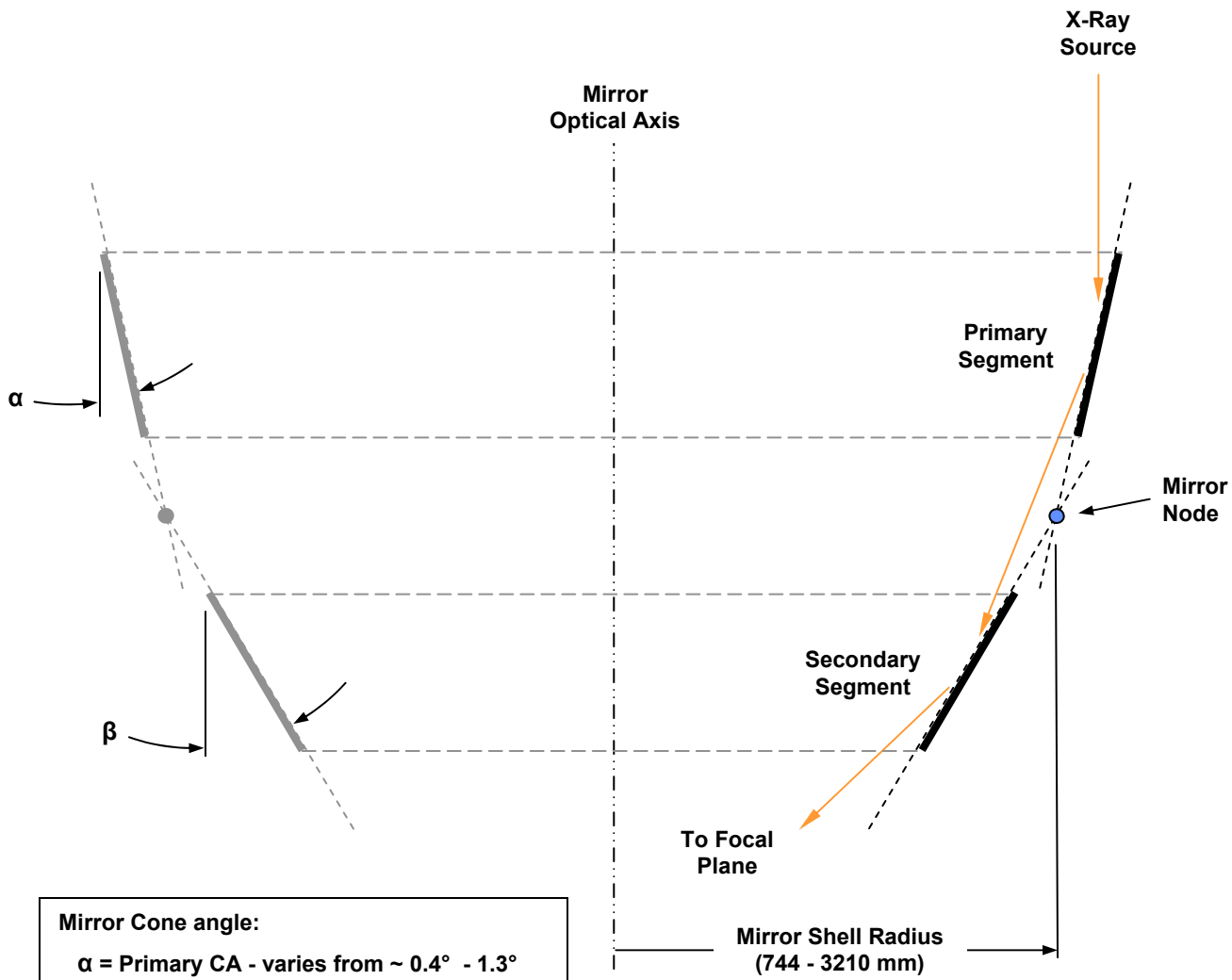
X-Ray Optic Primer

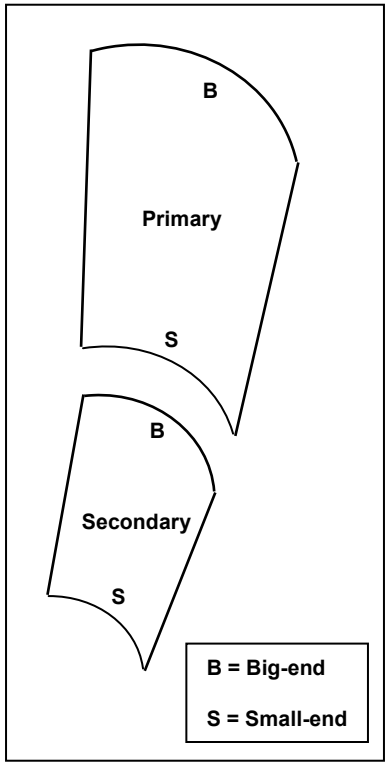
- Highly nested grazing incidence optics
  - If angle of incidence is too high, x-ray will be absorbed
  - Critical angle is dependent on energy of x-ray
- X-rays are focused by a primary and a secondary mirror
- Shells packed to increase collecting area
- Segmented mirror design





SXT Mirror Anatomy



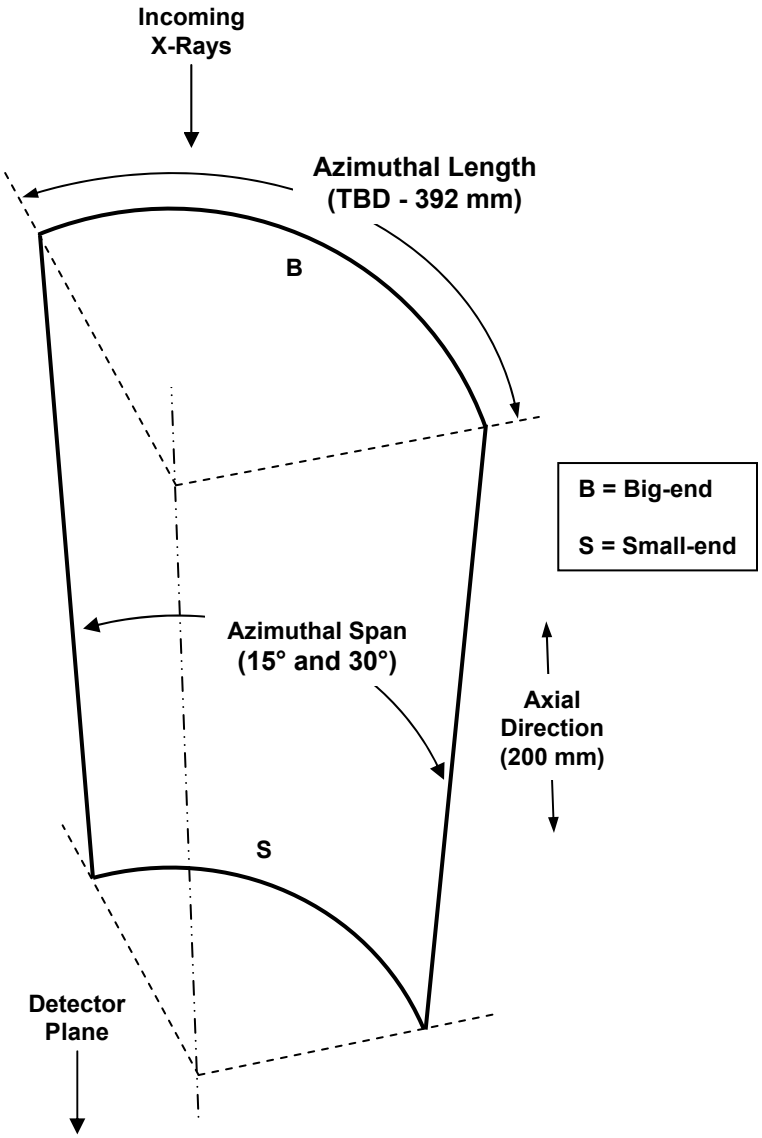


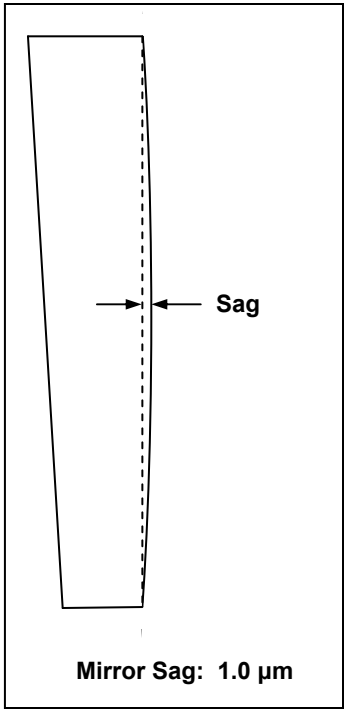
Mirror Cone angle:

α = Primary CA - varies from ~ 0.4° - 1.3°

β = Secondary CA - varies from ~ 1.2° - 3.6°

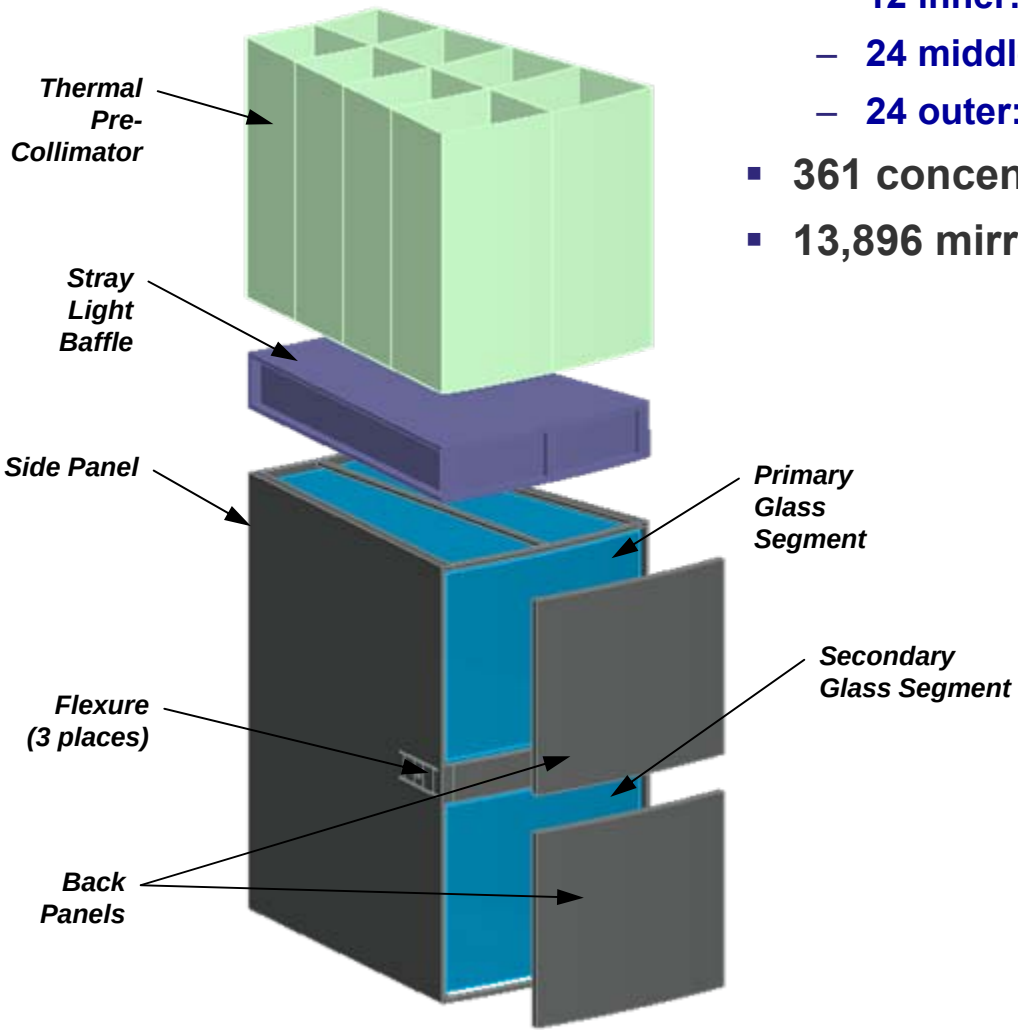
SXT Mirror Anatomy (cont'd)



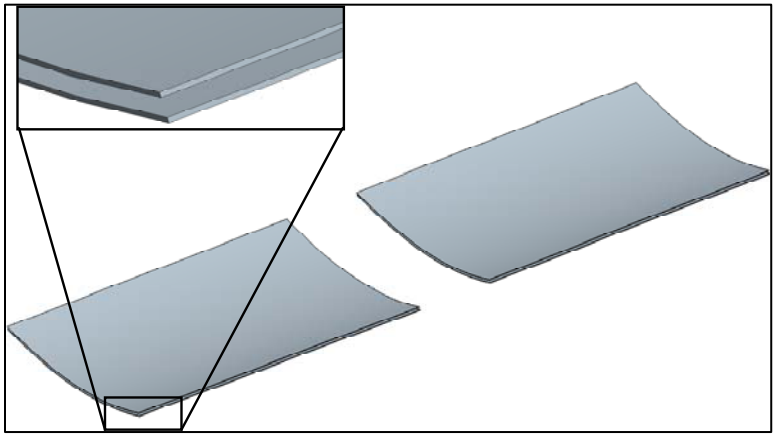


SXT Mirror Module

- Modular design: 60 modules
  - 12 inner: 143 mirror pairs
  - 24 middle: 115 mirror pairs
  - 24 outer: 103 mirror pairs
- 361 concentric shells (pairs)
- 13,896 mirror segments

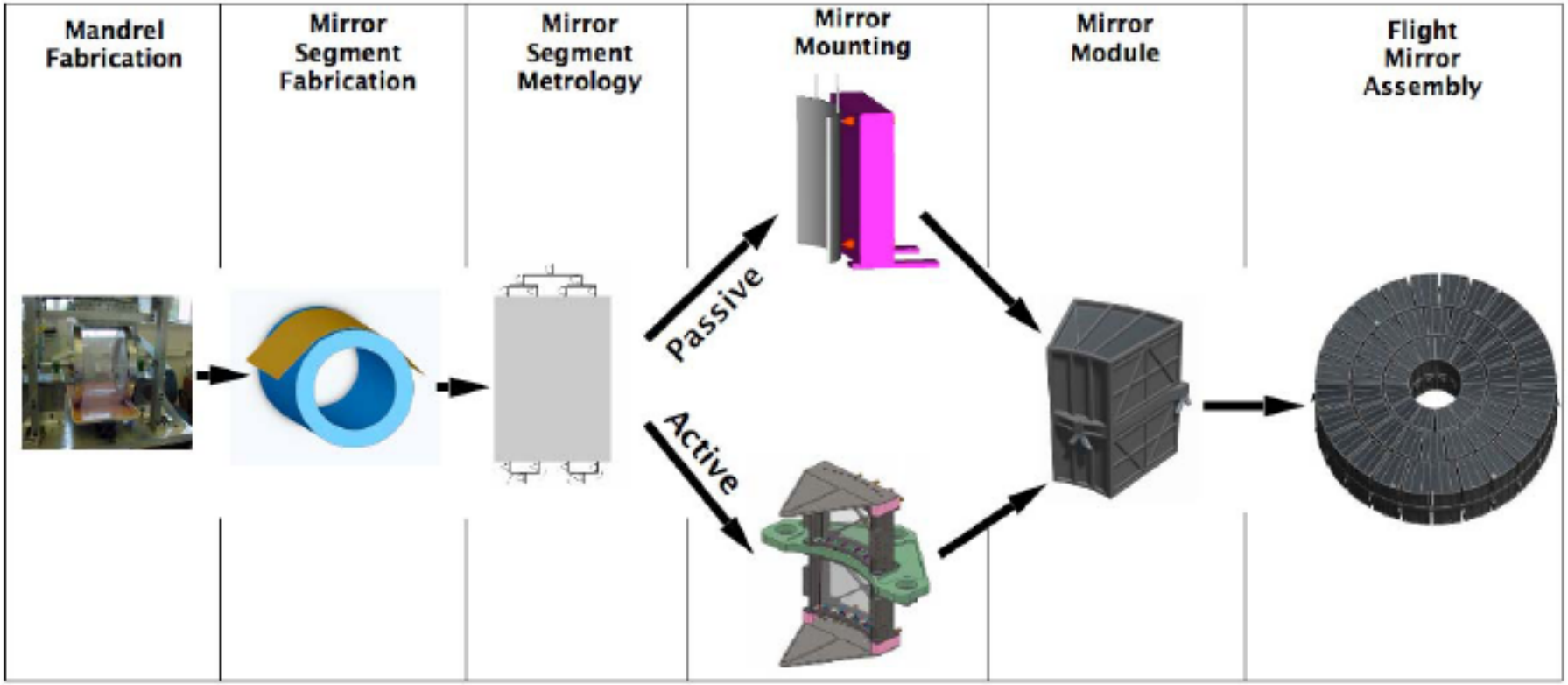


SXT Glass Mirror Segment



Nested Mirror Segments

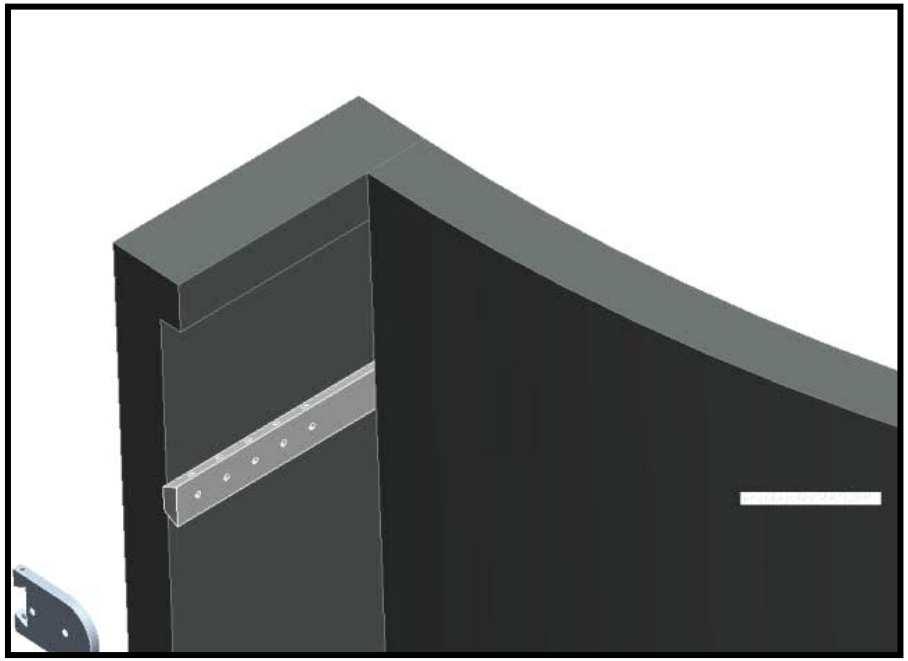
SXT Mirror Development



Mandrel Fabrication	Mirror Segment Fabrication	Mirror Segment Metrology	Mirror Mounting	Mirror Module	Flight Mirror Assembly
1. Figure quality	1. Replication fidelity	1. Mount distortion	1. Figure preservation or enhancement	1. Thermal distortion	1. Module integration
2. Metrology	2. Cutting accuracy	2. Accuracy	2. No. of bonding points	2. Gravity distortion	2. Gravity release
3. Production rate	3. Coating stress	3. Speed	3. Speed	3. Launch survivability	
4. Production cost				4. Long term stability	

SXT Mirror Bonding Steps

- **Primary and Secondary mirror segments bonded into the module:**
  1. **Nominally position tabs on the rails (6-8 tabs/segment)**
  2. **Nominally position and align a segment (via temporary mount)**
  3. **Adjust the tab positions to acquire the required gap to segment**
  4. **Bond the tabs to the rails**
  5. **Bond the segment to the tabs**
  6. **Release and retract the temporary mount**
  7. **Repeat steps 1-6 for another segment**



Bonding Process Video Clip

Traceability of Mission Reqt's to FMA Reqt's

Mission Performance Requirements that Drive FMA Requirements

Mirror Effective Area *	3 m^2 @1.25 keV 0.65 m^2 @ 6 keV 150 cm^2 @ 30 keV	Black hole evolution, large scale structure, cosmic feedback, Equation of State (EOS) Strong gravity, EOS Cosmic acceleration, strong gravity
Observatory Angular Resolution *	≤5 arc sec HPD <7 keV ≤30 arc sec HPD > 7 keV 5 arc sec HPD > 7 keV (Goal)	Large scale structure, cosmic feedback, black hole evolution, missing baryons Black hole evolution Cosmic X-ray Background (CXRB)
Energy Bandwidth	0.1 to ≥ 40 keV	Determination of continuum for measuring spin of accreting black holes Strong gravity CXRB studies

*** Reference N. White, Jan. 2009 presentation to AAS**

FMA Mass Budget

- **The FMA mass is a "live" allocation from the Observatory-Level - no mass requirements have been set yet**

FMA Summary Mass Information (kg)		
	Current Best Estimate Mass	**Maximum Expected Mass**
FMA Total Mass	**1748**	**2037**
Total SXT Glass Mass	733.2	843.2
Total SXT Module Structure Mass	482.1	561.2
Total SXT Thermal Heaters/Controllers	122.0	152.5
Total SXT Thermal Harness	19.8	30.7
Total Mass Supported by FMA Structure	1407.8	1646.2
Mass of FMA Structure	339.8	390.7
Total HXMM Mass	50.8	58.6

This column used to be carried as "X % Contingency" - Now based on Mass Growth Allowance per AIAA S-120-2006

FMA Power Budget

- The FMA power is a "live" allocation from the Observatory-Level - no power requirements have been set yet
- FMA power is supplied by an independent body-mounted solar panel (not coupled to S/C power)
- Thermal analysis is on-going - the Observatory and FMA models are converging

FMA Power Requirements		
Item No.	**Description**	**BOL**
1	**Observatory Estimate:** **Total FMA/SXT heaters (W)** Mirror Modules: Metering Structure:	 **1473** 1236 237
2	**FMA Estimate:** **Total FMA/SXT heaters (W)** Mirror Modules: Metering Structure:	 **1530** 1110 420
3	HXMM heaters (W)	10

Baseline Observatory Configuration:
- ***has heat pipes on S/C Adapter Ring***
- ***no FMA detail***

FMA Configuration:
- ***no heat pipes on S/C Adapter Ring***
- ***has module/SLB/Collimator details***

FMA Mechanical System Requirements

FMA Mechanical Requirements				
Item No.	**Description**			
1	Angular Resolution - FMA on-orbit (arcsec)			4.6
2	Effective Area	m^2	Goal (m^2)	keV
		3.0	---	1.25
		0.65	1.0	6
		0.015	0.035	30
3	FMA structure interface diameter - 24 bolts (m)			< 3.442
4	FMA envelope height FWD from S/C adapter plane (cm)			60
5	Optical System segment accomodation requirements			Various
6	HXMM mirror outer diameter (cm)			40
7	HXMM mirror inner diameter (cm)			20
8	FMA Mass (kg)	1748 (Current Best Estimate)		

Opto-Mechanical: optical design, co-alignment, stability, thermal distortion

Obscuration: loading, stiffness, etc.

FMA forward structural envelope

Driven by the Optical Design

HXMM module radial footprint

See Chart 12

FMA Thermal System Requirements

FMA Thermal-Related Requirements		
Item No.	**Description**	
1 *	FMA/SXT operating temperature (°C)	20 ± 1
2 *	SXT Module gradient - axially, azimuthally (ΔT)	< 1.0
3	HXMM operating temperature (°C)	20 ± 0.5
4	HXMM gradient - axially, azimuthally (ΔT)	< 0.5
5	FMA Survival Temperatures (°C)	10 minimum 30 maximum

Derived by analysis for the previous 15 arcsec mirror

Adapted from NUSTAR experience

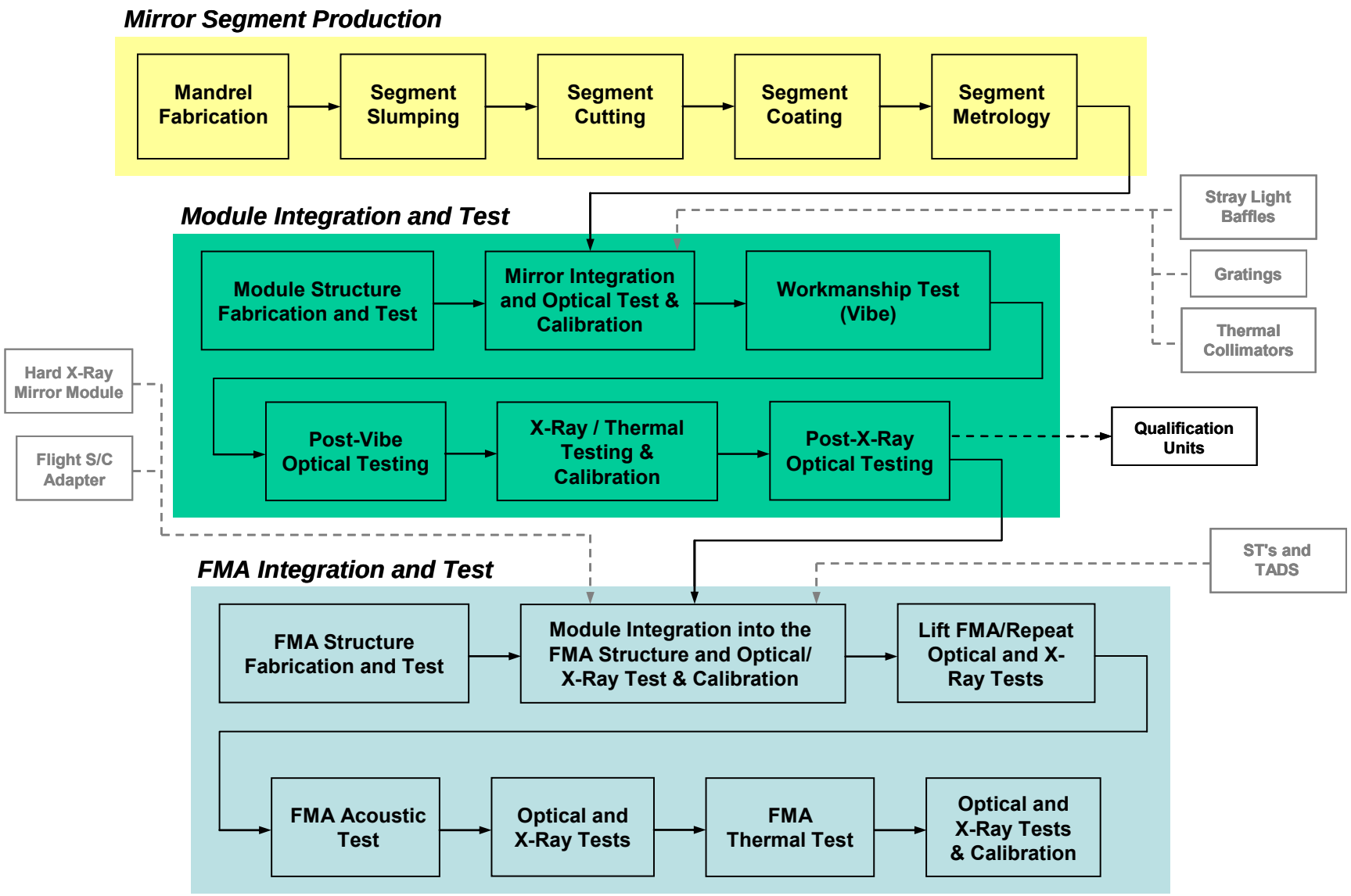
Derived from Chandra experience

**** These thermal requirements are derived from the 1.0 arcsec HPD gradient thermal distortion requirement, and will be verified via STOP analysis of the opto-mechanical design. They may need to be modified as the thermal distortion effects are modeled.***

FMA Contamination Requirements

- **Contamination:**
  - **Review and assess Chandra requirements, and add additional requirements, to establish a baseline for the FMA**
  - **Assign an FMA Contamination Expert to further define requirements**
  - **Known contamination elements:**
    - **The FMA will have covers on each side**
    - **The FMA will be purged**
    - **Tents/covers will be employed during integration to protect from FOD and contamination**

FMA Integration and Test Flow

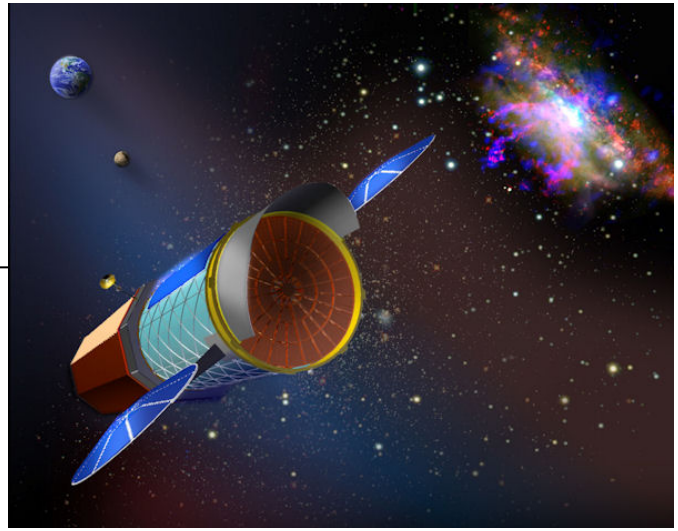


FMA Technical Interchange Meeting
March 9, 2009 / GSFC

FMA Structure Design and Analysis

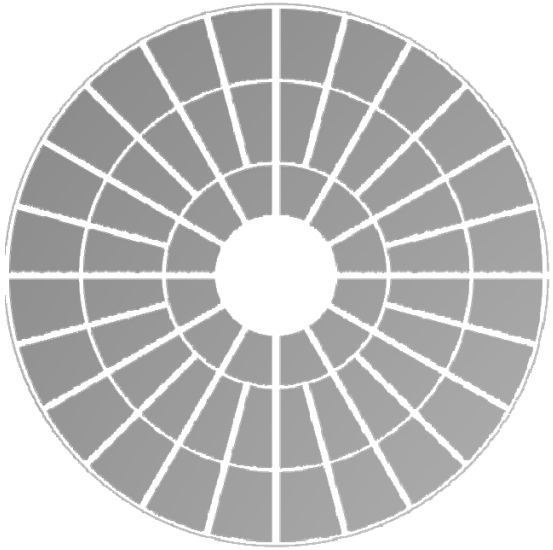
David Robinson/543

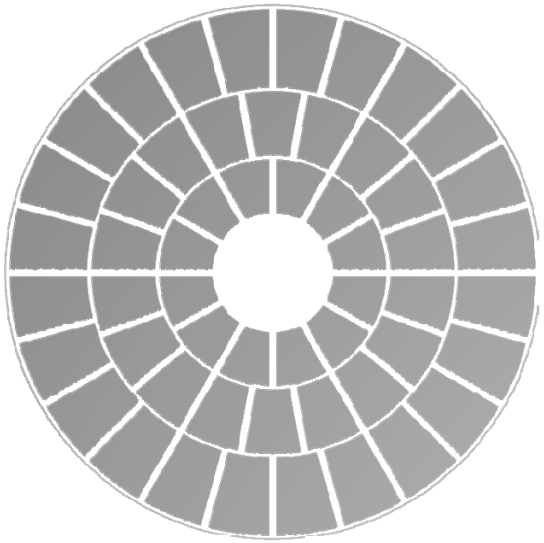
Ryan McClelland / SGT



SXT Module Layout

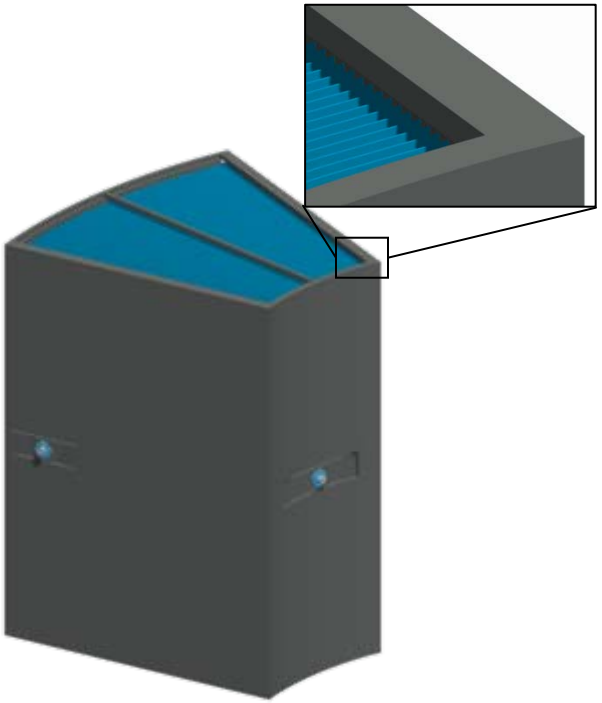
- Layout consists of three rings of modules, 12 inner, 24 middle, and 24 outer = 60 total
  - Based on trade studies
- Modules are a 'handle-able' size
  - Less than 30 kg
  - Enveloping dimensions of all modules 650 mm x 500 mm x 450 mm
- Radial spaces between modules avoid peak 6 keV energy efficiency
- Limits largest segment needed to < 400 mm, a limitation of the 0.4 mm glass sheets available
- Provides a good load path from modules to spacecraft due to 12-fold symmetry
  - 12/18/24 layout was also considered, but discarded due to poor load path
  - FEA shows that the 12/24/24 layout yields a 25% lighter structure due to superior load path

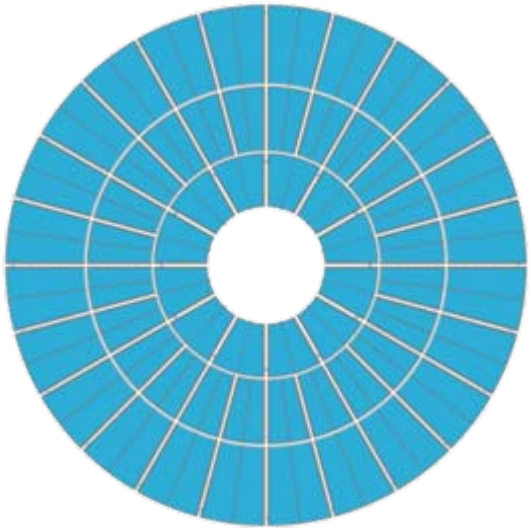




Advantages of Modular Approach

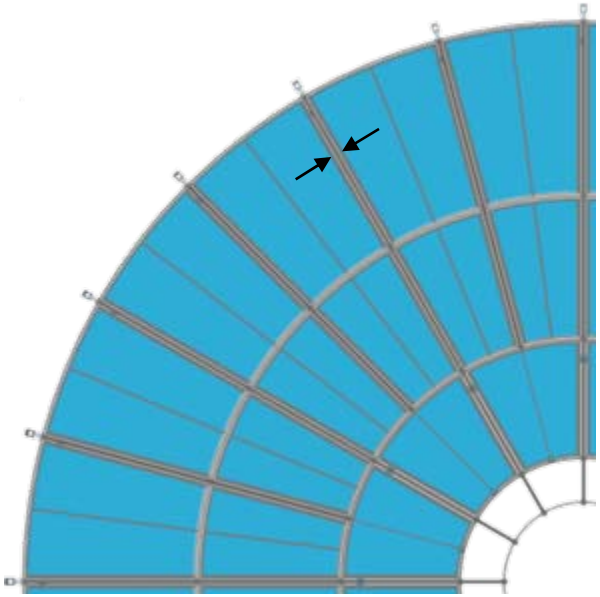
- **Reduces risk**
  - If one segment or set of segments is damaged before launch, the module can be replaced
- **Allows for easier handling**
  - Modules are designed to be a manageable size for assembly, transportation, and test
- **Reduces FMA fabrication time**
  - Since integrating large numbers of segments will be time consuming, the modular approach allows for parallel assembly
- **Reduces load in mirror segments**
  - Kinematically mounted modules take segments out of primary load path
- **Reduces thermal distortion of mirror segments**
  - Kinematically mounted modules decouple the deformation of the primary structure from the deformation of the segments
- **Approach is applicable to X-ray mirrors of arbitrary size**
  - If the FMA size changes in future observatory design iterations, technology developed to create a module is still directly applicable

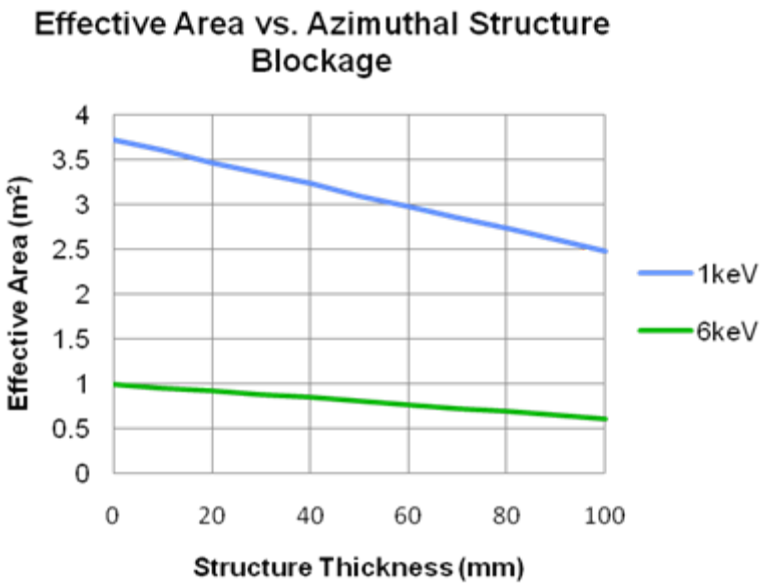




SXT Effective Area Performance

- FMA design optimized to maximize SXT effective area
- 46 mm of azimuthal structural per module
- 46 mm radial gap between module rings
- 3.2 m^2 at 1.25 keV
  - 15% loss due to structure
- 0.8 m^2 at 6.0 keV
  - 18% loss due to structure



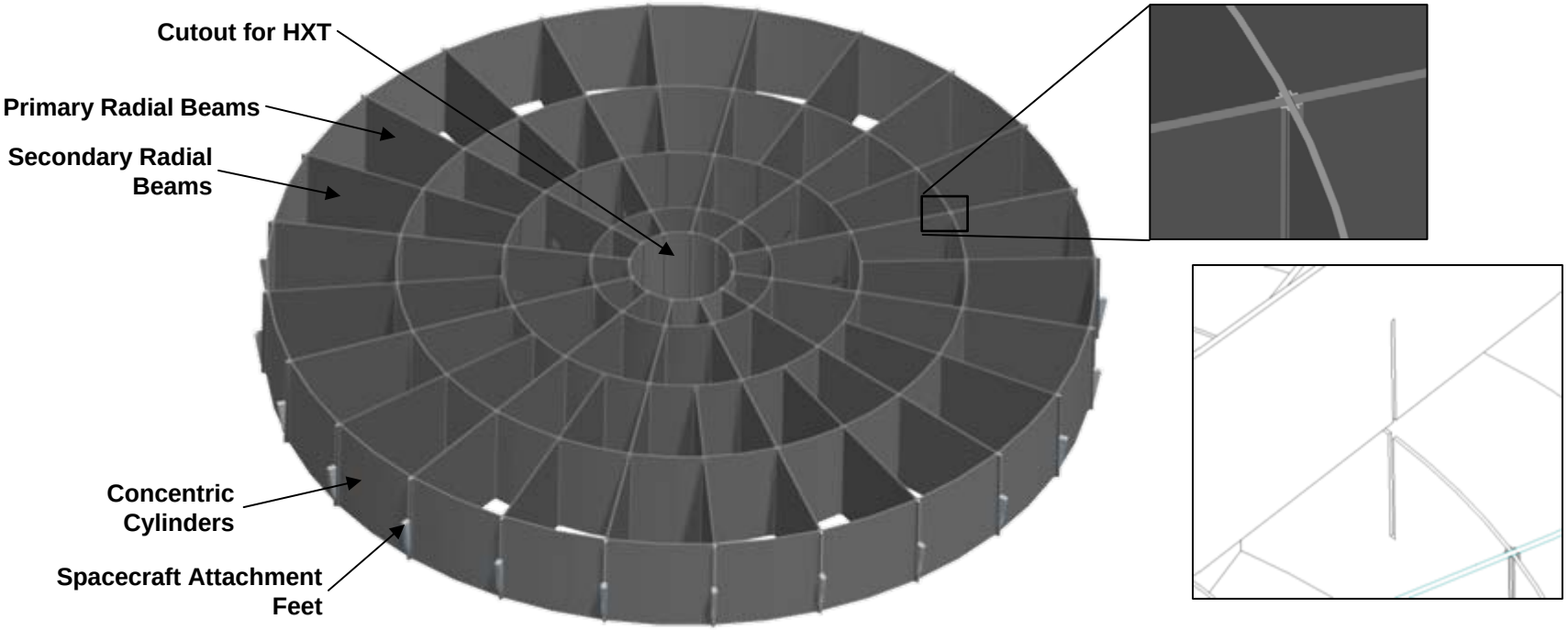


Azimuthal Structure

Source	Amount (mm)
Primary structure	10
Module structure	5 x 2 = 10
Gap between primary structure and module structure	2 x 2 = 4
Gap between module structure and mirror edge	2 x 2 = 4
Bonding points	3 x 6 = 18
Total	**46**

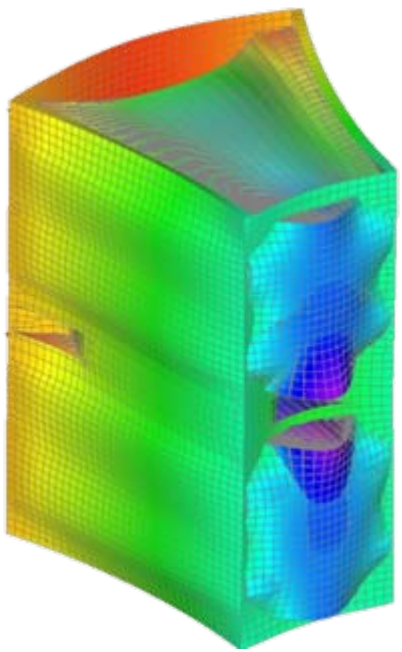
FMA Primary Structure

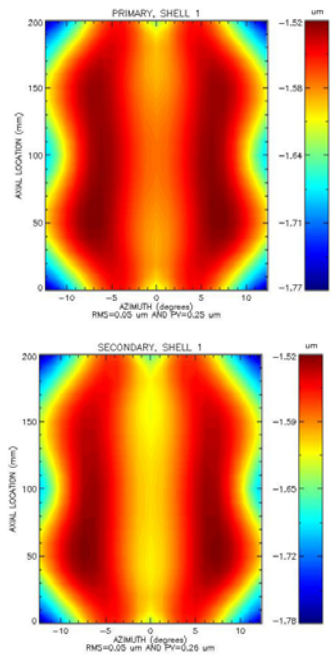
- Carrier structure supporting 60 kinematically mounted modules totaling ~1300 kg
- Constructed using standard aerospace materials and design practices
- All structural members made from M55J/954-3 Carbon Fiber Reinforced Plastic (CFRP) for high stiffness, low weight, and near-zero CTE
- Primary and secondary radial beams of rectangular cross sections
  - Minimizes beam thickness and maximizes effective area
- Radial beams connected by concentric cylinders
- Bonded 'wine-box' construction with doublers in corners

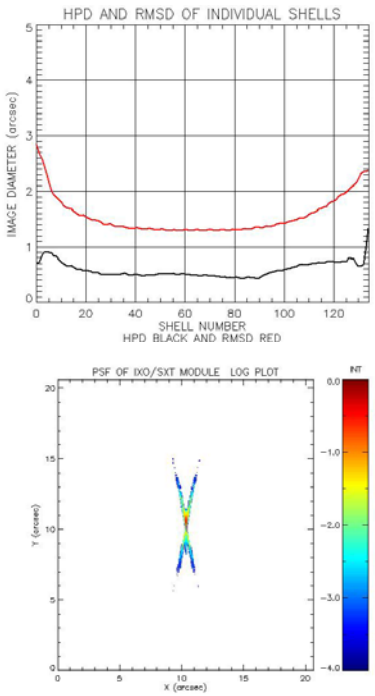


SXT Module Design (cont.)

- **Module structure made from Titanium/Molybdenum alloy with CTE matching D263 mirror segments (CTE 6.2 ppm/C)**
- **Optomechanical analysis of module with segments in work**
  - **FEMs of all 200-300 segments in module generated from optical prescription using custom software**
  - **Thermal and gravity distortion cases run using NASTRAN**
  - **Performance prediction generated based on deformed model is using custom ray tracing software**
  - **1°C bulk temperature change case => performance prediction 0.6 arc-sec HPD**

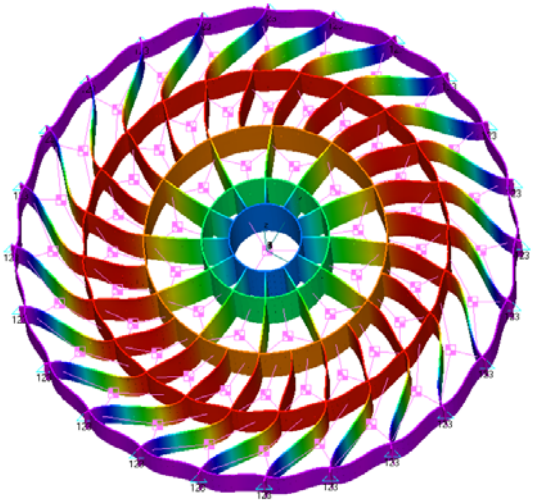


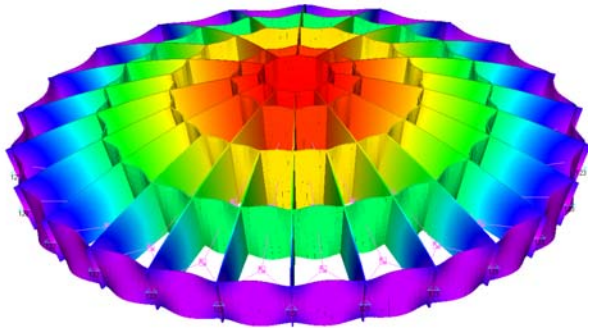


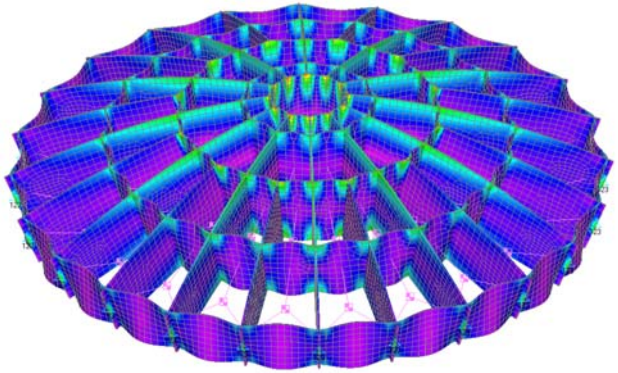


FMA Primary Structure (cont)

- **FEM description**
  - Members modeled with plate elements assuming isotropic CFRP layup
  - Modules modeled as lump masses with kinematic mounts
    - Assumes modules do not add stiffness to structure (conservative)
  - 3 DOF constraints at bolted interface to spacecraft
  - Member thicknesses optimized using NASTRAN SOL200
- **Design performance**
  - Structural mass 28% of payload (module) mass
  - 16 Hz first torsional mode
  - 60 Hz first axial mode
  - 1 G axial load maximum displacement 0.1 mm
  - 10 G axial load maximum stress 30 MPa (4.4 ksi)
  - 10 G lateral load maximum stress 47 MPa (6.8 ksi)
  - Maximum interface force 15,700 N (3500 lb) due to 10 G lateral load
  - 1°C bulk temperature change distortion 0.002 mm
- **Significant room for optimization remains!**

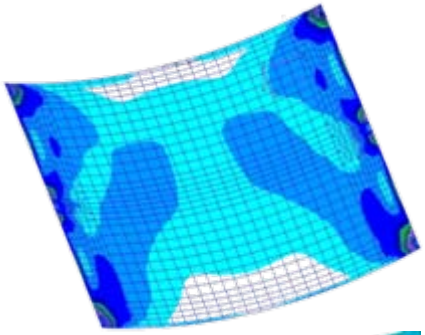


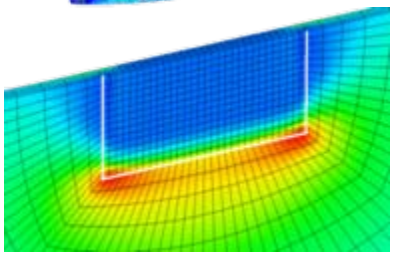


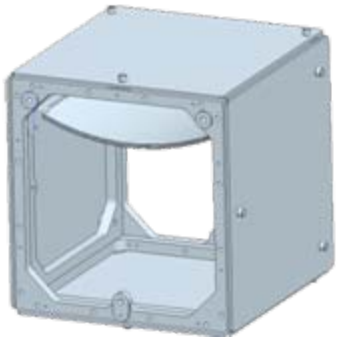


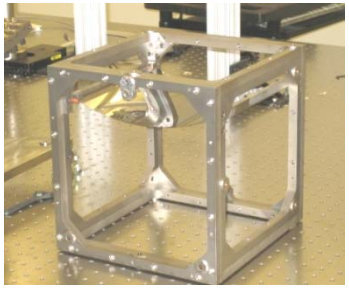
SXT Mirror Segment Survivability

- **Materials testing, FEM analysis, and mounted mirror segment environmental testing indicate glass can survive launch**
- **Glass strength is sufficient for survivability**
  - **FEA of baseline design give positive margin vs. allowable developed from materials testing**
  - **Optimization of size and number of bond points in work**
- **Environmental testing of mirror segments bonded in permanent housing completed**
  - **Acoustic test of three segments in housing representing module up to Atlas 551 qualification levels (2 minutes at 143.3 dB)**
  - **Successfully completed random vibration and acoustic tests of single mirror in Cube housing**
    - **Mirror optical figure did not change throughout testing**
  - **Good correlation between test results and analysis**
- **Will continue environmental tests of development platforms to retire survivability risks**





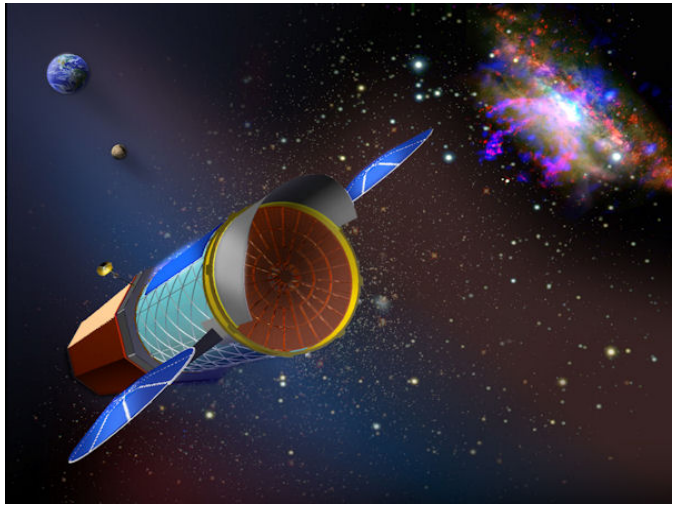




IXO Table Top Review

2009 03 12
NASA GSFC, Bldg 23, Room C130D

Instruments Overview



Tom Buckler/GSFC
Project Systems Engineer

Instrument Operation/Science Mode Summary

		Science Modes			
		Mode 1	Mode 2	Mode 3	Mode 4
Instrument Operations	Science	XMS, XGS	WFI, HXI, XGS	X-Pol, XGS	HTRS, XGS
	Standby	WFI, HXI, X-Pol, HTRS	XMS, X-Pol, HTRS	WFI, HXI, HTRS, XMS	WFI, HXI, XMS, X-Pol
Observation Duration (hours)	Average	10 hours			
	Minimum	30 minutes			
	Peak	48 hours			
Percent time for each Mode		40%	40%	10%	10%

Payload Mass, Power, and Data Rate Summary

Power (W)												
Element	Mass (kg)	Ave	Peak	Standby	Mode 1		Mode 2		Mode 3		Mode 4	
					Ave	Peak	Ave	Peak	Ave	Peak	Ave	Peak
FMA	1741.0	1394.0	1394.0	1394.0	1394.0	1394.0	1394.0	1394.0	1394.0	1394.0	1394.0	1394.0
XMS	256.6	649.0	703.0	322.8	649.0	703.0	322.8	322.8	322.8	322.8	322.8	322.8
(WF&HX)I	98.6	268.9	268.9	30.2	30.2	30.2	268.9	268.9	30.2	30.2	30.2	30.2
XGS	39.7	96.3	98.5	35.0	96.3	98.5	96.3	98.5	96.3	98.5	96.3	98.5
XPOL	10.5	36.0	36.0	0.0	0.0	0.0	0.0	0.0	36.0	36.0	0.0	0.0
HTRS	25.1	94.3	94.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	94.3	94.3
Total	**2135.9**				**2169.5**	**2225.7**	**2082.0**	**2084.2**	**1879.3**	**1881.5**	**1937.6**	**1939.8**

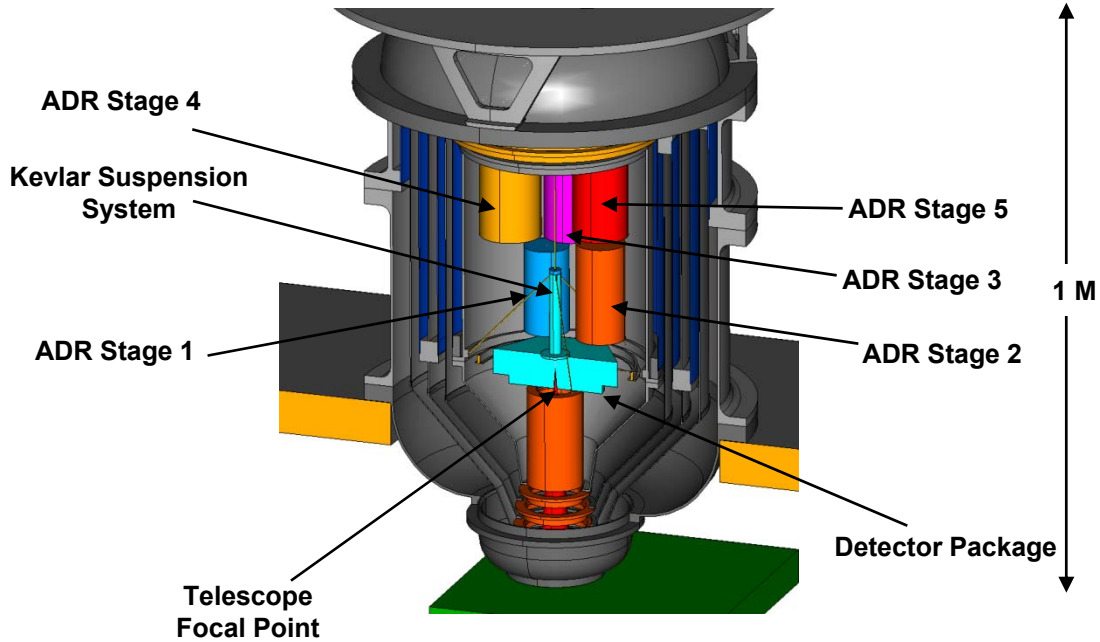
Data Rate (Kbps)												
Element		Ave	Peak	House-Keeping	Mode 1		Mode 2		Mode 3		Mode 4	
					Ave	Peak	Ave	Peak	Ave	Peak	Ave	Peak
FMA		1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
XMS		29.6	1684.0	4.0	29.6	1684.0	4.0	4.0	4.0	4.0	4.0	4.0
(WF&HX)I		56.0	2001.0	0.8	0.8	0.2	56.0	2001.0	0.2	0.2	0.2	0.2
XGS		151.0	1501.0	1.0	1501.0	151.0	151.0	1501.0	151.0	1501.0	151.0	1501.0
XPOL		300.2	1000.2	0.2	0.2	0.2	0.2	0.2	300.2	1000.2	0.2	0.2
HTRS		50.2	50.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	50.2	50.2
Total					**1532.8**	**1836.6**	**212.4**	**3507.4**	**456.6**	**2506.6**	**206.6**	**1556.6**

X-ray Microcalorimeter Spectrometer (XMS)

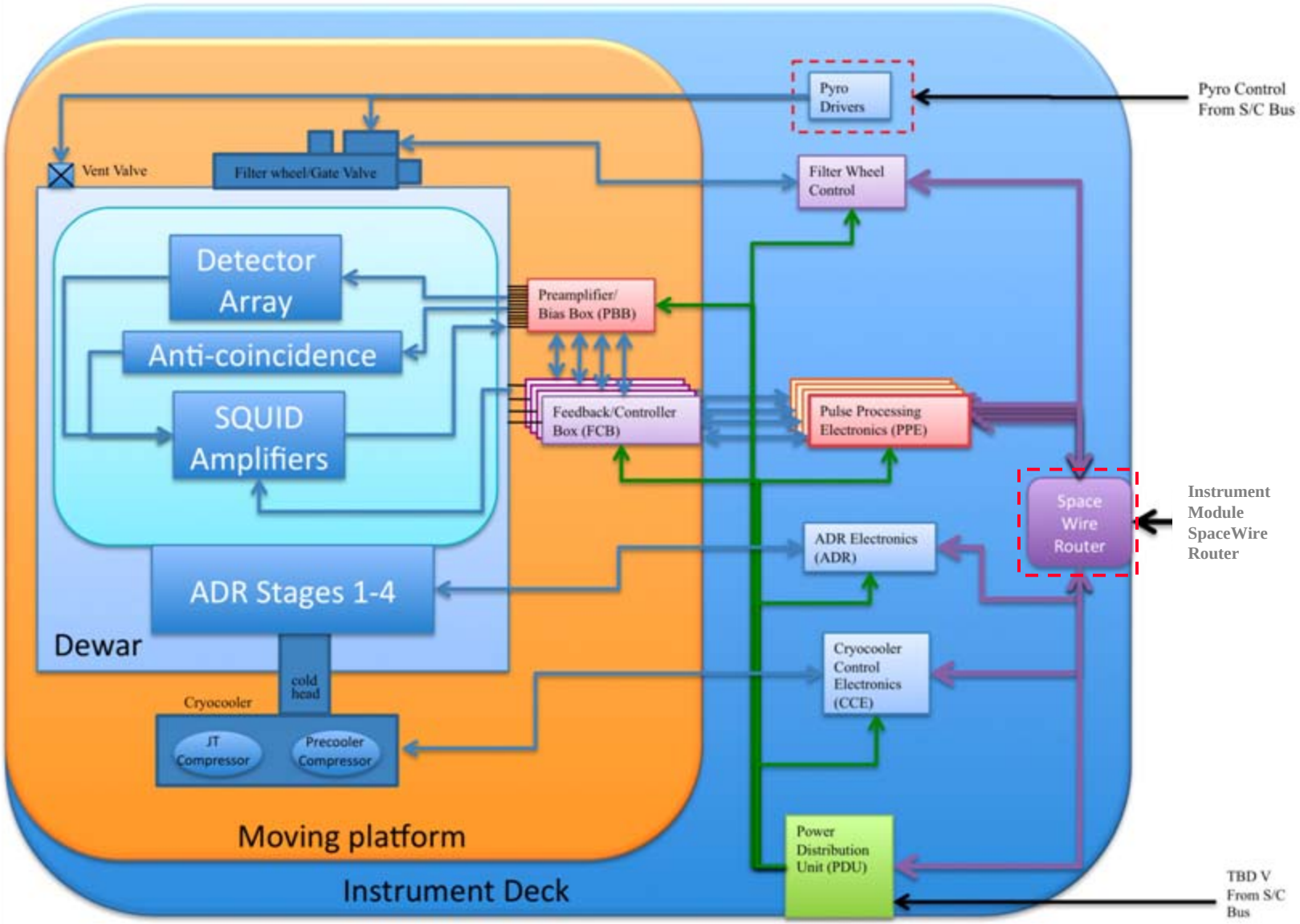
- **Imaging Spectrometer:**

- **Key Performance Requirements**
  - Bandpass: 0.6 to 10 keV
  - Spectral Resolution:
    - 2.5 eV < 6keV for FOV 2 arcmin
    - 15 eV < 6kev for FOV 5.4 arcmin

- **Features**
  - Transition Edge Sensor microcalorimeter
  - Array size configured with:
    - 2 arcmin inner "high resolution" array, 40x40 pixels @ 300µm pixel size
    - 5.4 arcmin "extended field" array
  - Photon counting device
  - Detector operates at 50 mK
    - Cooled by multistage ADR in series with mechanical cryocooler
    - No expendable cryogens
  - Data Rate: 41 kbps (ave), 1681 kbps (peak)



XMS Block Diagram



Provided by spacecraft

XMS Mechanical Interface Requirements*

Mechanical Interface Requirements (Current Best Estimate - No Margin)					
Payload Element		Dimen (cm) H x W x D	Mass (kg)	Location	Comments / Source
XMS	Dewar Assembly	100x75 Dia	174.5	At FMA focus, on MIP	Include cryocooler and compressor
	Filter Wheel	21X64X40	6.0	Mounted to dewar shell, forward end	
	Pre-Amplifier/BiasBox (PBB)	15x23x20	3.8	<1 m from dewar	
	Feedback/Controller Box (FCB) -1	23x28x20	4.8	<1 m from dewar	
	Feedback/Controller Box (FCB) -2	23x28x20	4.8	<1 m from dewar	
	Feedback/Controller Box (FCB) -3	23x28x20	4.8	<1 m from dewar	
	Feedback/Controller Box (FCB) -4	23x28x20	4.8	<1 m from dewar	
	Sub-Total MIP		**203.5**		
	Pulse Processing Electronics (PPE)	28x28x20	13.6	<several m from dewar	
	ADR Controller (ADRC)	13x25x38	8.5	<several m from dewar	
	Cryocooler Control Electronics (CCE)	20x20x20	10.0	<several m from dewar	2 cards 1 box
	Filter Wheel Control Electronics (FWC)	25x20x5	6.0	<several m from dewar	
	Power Distribution Unit (PDU) -1	25x38x20	10.0	<several m from dewar	
	Power Distribution Unit (PDU) -2	20x38x20	5.0	<several m from dewar	
	Sub-Total FIP		**53.1**		
	TOTAL XMS		**256.6**		

Harness mass included in observatory harness mass

XMS Thermal Interface Requirements

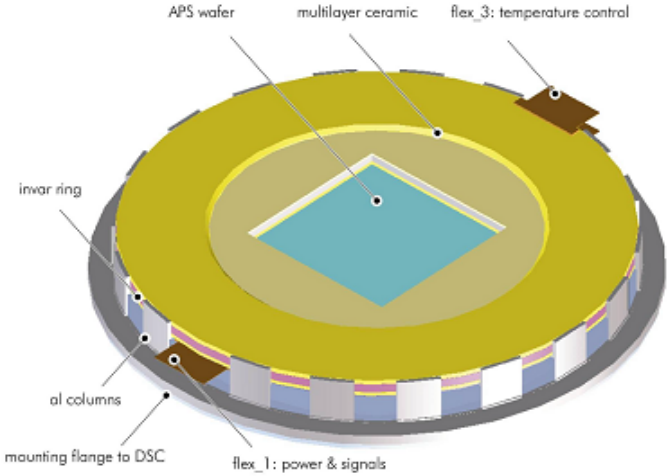
Instrument Thermal Interface Requirements					
Payload	**Element**	**Operating**	**Annealing**	**Survival - (Off)**	**Comments / Source**
XMS	Dewar Assembly	-33C to 27C		-100C to 50C	**CDF = 20C**
	Filter Wheel	-20C to 50C		-20C to 50C	
	Pre-Amplifier/BiasBox (PBB)	-20C to 50C		-30C to 70C	
	Feedback/Controller Box (FCB) -1	-20C to 50C		-30C to 70C	
	Feedback/Controller Box (FCB) -2	-20C to 50C		-30C to 70C	
	Feedback/Controller Box (FCB) -3	-20C to 50C		-30C to 70C	
	Feedback/Controller Box (FCB) -4	-20C to 50C		-30C to 70C	
	Pulse Processing Electronics (PPE)	-20C to 50C		-30C to 70C	
	ADR Controller (ADRC)	7C to 27C		-30C to 70C	
	Cryocooler Compressor	10C to 40C		-20C to 50C	
	Cryocooler Control Electronics (CCE)	10C to 40C		-30C to 70C	
	Filter Wheel Control Electronics (FWC)	10C to 40C		-30C to 70C	
	Power Distribution Unit (PDU) -1	10C to 40C		-30C to 70C	
	Power Distribution Unit (PDU) -2	10C to 40C		-30C to 70C	

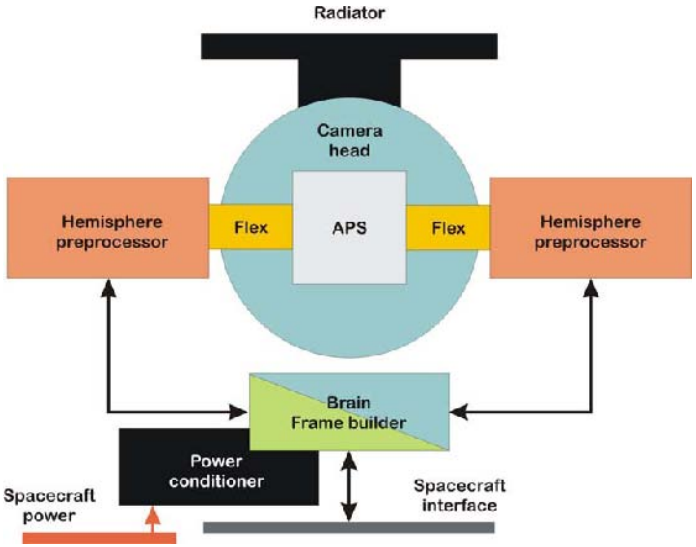
XMS Power Interface Requirements

Instrument Power Interface (Current Best Estimate - No Margin)							
Instrument	Element	Power (W)					Comments /Source
		Average	Peak	Annealing	Standby - Sleep	Safe Hold - Off	
XMS	Dewar Assembly	215.0	215.0	0.0	215.0	0.0	Include cryocooler and compressor
	Pre-Amplifier/BiasBox (PBB)	24.8	24.8	0.0	0.0	0.0	
	Feedback/Controller Box (FCB) -1	45.0	55.0	0.0	0.0	0.0	
	Feedback/Controller Box (FCB) -2	45.0	55.0	0.0	0.0	0.0	
	Feedback/Controller Box (FCB) -3	45.0	55.0	0.0	0.0	0.0	
	Feedback/Controller Box (FCB) -4	45.0	55.0	0.0	0.0	0.0	
	Pulse Processing Electronics (PPE)	62.0	62.0	0.0	0.0	0.0	
	ADR Controller (ADRC)	5.0	8.0	0.0	0.0	0.0	
	Cryocooler Control Electronics (CCE)	54.0	54.0	0.0	54.0	0.0	
	Filter Wheel Control Electronics (FWC)	0.0	2.0	0.0	0.0	0.0	
	Total (before power losses) for PDU 1	266.8	306.8	0.0	0.0	0.0	Includes PBB, FCB-1 - 4, PPE
	Total (before power losses) for PDU 2	274.0	279.0	0.0	269.0	0.0	Includes dewar, ARDC, CCE
	Power Distribution Unit (PDU) -1	53.4	61.4	0.0	0.0	0.0	Dissipation for 80% eff.
	Power Distribution Unit (PDU) -2	54.8	55.8	0.0	53.8	0.0	Dissipation for 80% eff.
	Total XMS	**649.0**	**703.0**	**0.0**	**322.8**	**0.0**	

Wide Field & Hard X-Ray Imager (WF&HX)I

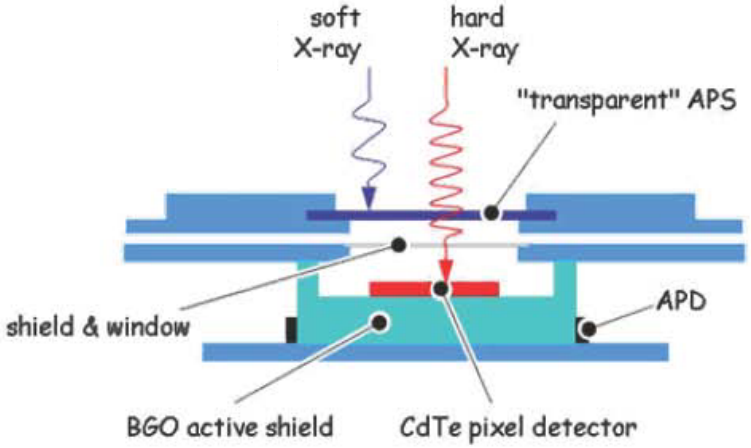
- Two Imaging spectrometers
- Key Performance Requirements
  - WFI Bandpass: 0.1 to 15 keV
  - WFI Field of View: 18 arcmin circular
  - HXI Extends Bandpass to 40 keV
  - HXI Field of View: 12 arcmin circular
- WFI Features
  - Silicon array of Active Pixels
  - Single chip 1024 x 1024; pixel pitch 100 um
  - Array size 102 x 102 mm2
  - Individual pixel access
  - Detector temperature -63 C ± 0.1 C
  - Data Rate: 45 kbps (ave); 1000 (peak)

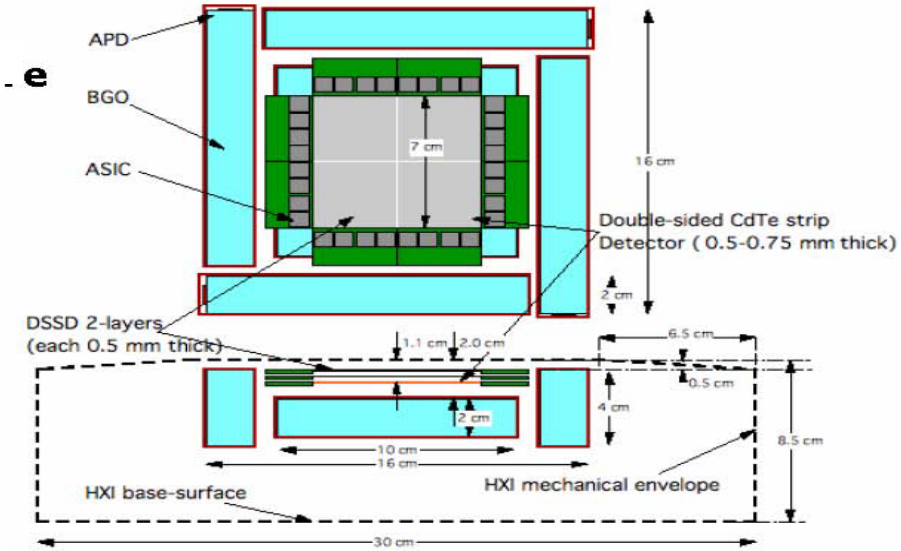




Hard X-ray Imager Wide Field & Hard X-Ray Imager (WF&HX)I Cont.

- **HXI Features**
  - Based on Si + CdTe double sided strip detectors
  - Mounts behind WFI detector within WFI envelope
  - Detector temperature: -20 C ± 2 C
  - Requires regular annealing at 5 ± 2 C
  - Data Rate: 11 kbps (ave); 1001 kbps (peak)
  - Room temperature electronics
  - Baffle required





(WF & HX)I Mechanical Interface Requirements

Mechanical Interface Requirements (Current Best Estimate - No Margin)					
Payload Element		**Dim (cm)** H x W x D	**Mass (kg)**	**Location**	**Comments / Source**
(WF&HX)I	Focal Plane Assembly [(WF&HX)I-FPA]	21.5x32x70	41.0	On MIP - detector at mirror focus	Mass includes camera head (with radiation shield, cables, door and interfaces to radiator), filter sled and flex brackets. Baffle required
	HXI Sensor Head (HXI-S)	30x30x8.5	12.0	On MP _ Within WFI assembly (behind and coaligned with WFI)	
	Cold Part (-63C)				
	Warm Part (17 C)				Flex Brackets (2)
	WFI Hemisphere Pre-Processor-1	35x25x25	5.8	On MIP < several meters from Camera Head	2 modules, one for each hemisphere (includes boxes).
	WFI Hemisphere Pre-Processor-2	35x25x25	5.8	On MIP < several meters from Camera Head	2 modules, one for each hemisphere (includes boxes).
	HXI Analog Electronic Unit (HXI-EA)	20x20x10	4.0	On MIP < 10cm from focal plane	
	Sub-Total MIP		**68.6**		
	WFI Brain Frame Builder-1&2	35x50x25	11.0	On FIP < several meters from Camera Head	2 redundant modules, (included in single box)
	WFI Power Conditioner-1	35x25x25	5.5	On FIP < several meters from Camera Head	
	WFI Power Conditioner-2	35x25x25	5.5	On FIP < several meters from Camera Head	
	HXI Digital Electronics (HXI-DE)	20x20x10	4.0	On FIP < 100cm from focal plane	
	HXI PSU (HXI PSU)	20x20x10	4.0	On FIP < 100cm from focal plane	
	Sub-Total FIP		**30.0**		
	Total (WF&HX)I		**98.6**		

(WF&HX)I Thermal Interface Requirements

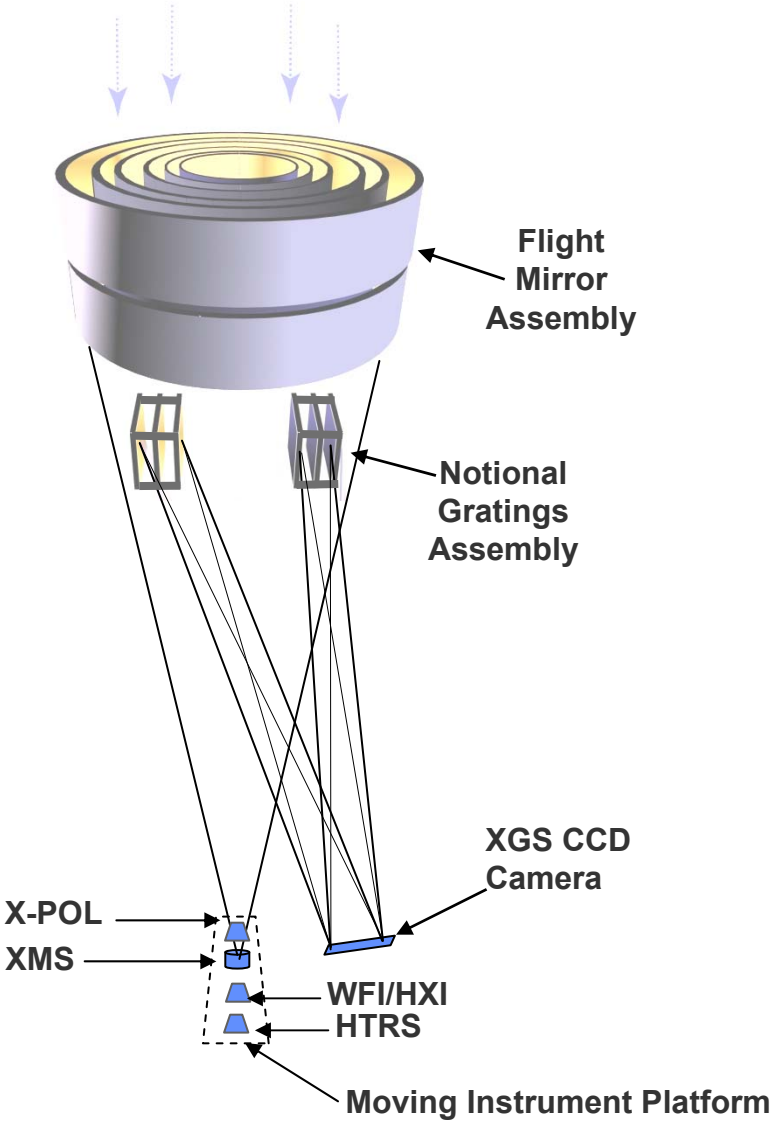
Instrument Thermal Interface Requirements					
Payload	**Element**	**Operating**	**Annealing**	**Survival - (Off)**	**Comments / Source**
(WF&HX)I	Focal Plane Assembly [(WF&HX)I-FPA]				
	Focal Plane Assembly - cold part	-63 +/- 0.1 C		-103 to 77 C	Thermal isolation required between camera and deck. Cooling is assumed to be through cold finger to radiator + local heater regulator. Provide 10C colder interface for detector (i.e. -73 C)
	Focal Plane Assembly - warm part	0 to 40 C		-40 to +85 C	Flex Brackets (2)
	HXI Sensor Head (HXI-S)	-20 +/- 2 C	5 ±2 C	-40 to +40 C	Internal to WFI-FPA - Set by Instrument
	WFI Hemisphere Pre-Processor-1	0 to 40 C		-40 to +85 C	
	WFI Hemisphere Pre-Processor-2	0 to 40 C		-40 to +85 C	
	HXI Analog Electronic Unit (HXI EA)	0C to 40 C	0C to 40 C	-40 to +40 C	
	WFI Brain Frame Builder-1&2	0 to 40 C		-40 to +85 C	
	WFI Power Conditioner-1 (control)	0 to 40 C		-40 to +85 C	
	WFI Power Conditioner-2 (control)	0 to 40 C		-40 to +85 C	
	HXI Digital Electronics (HXI DE)	0C to 40 C	0C to 40 C	-40 to +40 C	
	HXI PSU (HXI PSU)	0C to 40 C	0C to 40 C	-40 to +40 C	

(WF&HX)I Power Interface Requirements

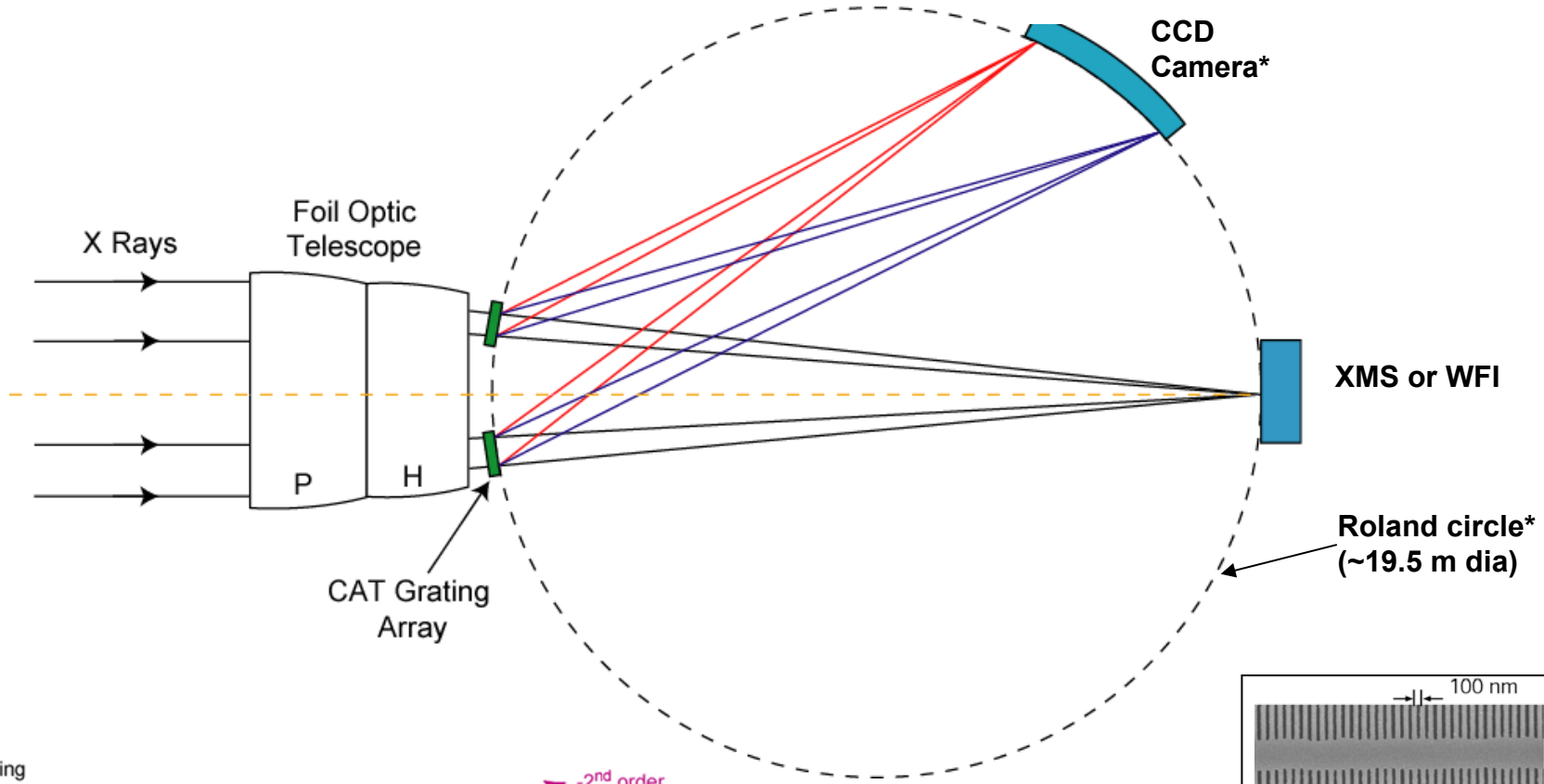
Instrument Power Interface (Current Best Estimate - No Margin)							
Instrument	Element	Power (W)					Comments /Source
		Average	Peak	Annealing	Standby - Sleep	Safe Hold - Off	
(WF&HX)I	Focal Plane Assembly (FPA)						Includes camera head (with radiation shield, cables, door and interfaces to radiator), filter sled and flex brackets.
	Cold Part	25.1	25.1			0.0	
	Warm Part	18.1	18.1			0.0	
	HXI Sensor Head (HXI-S)	4.2	4.2	25.0	3.5	0.0	
	Sub-Total (FPA)	**47.3**	**47.3**	**25.0**	**3.5**		
	WFI Hemisphere Pre-Processor-1 (WFI-HPP1)	47.0	47.0			0.0	Includes ADC cluster
	WFI Hemisphere Pre-Processor-2 (WFI-HPP2)	47.0	47.0			0.0	Includes ADC cluster
	HXI Analog Electronic Unit (HXI EA)	10.8	10.8	10.8	0.0	0.0	
	Sub-Total MIP	**104.8**	**104.8**	**10.8**	**0.0**		
	WFI Brain/Frame Builder-1&2	20.0	20.0		12.0	0.0	Includes image controller
	WFI Power Conditioner-1 (WFI-PCU1)	75.9	75.9		13.7	0.0	Conversion losses for 30% eff. Dc-dc conversion
	WFI Power Conditioner-2 (WFI-PCU2)	0.0	0.0		0.0	0.0	Redundant Unit - Conversion losses for 30% eff. Dc-dc conversion
	HXI Digital Electronics (HXI DE)	7.5	7.5	7.5	0.0	0.0	
	HXI PSU (HXI PSU)	13.3	13.3	22.3	1.0	0.0	
	Sub-Total FIP	**116.8**	**116.8**	**29.8**	**26.7**	**0.0**	
	Total (WF&HX)I	**268.9**	**268.9**	**65.6**	**30.2**	**0.0**	

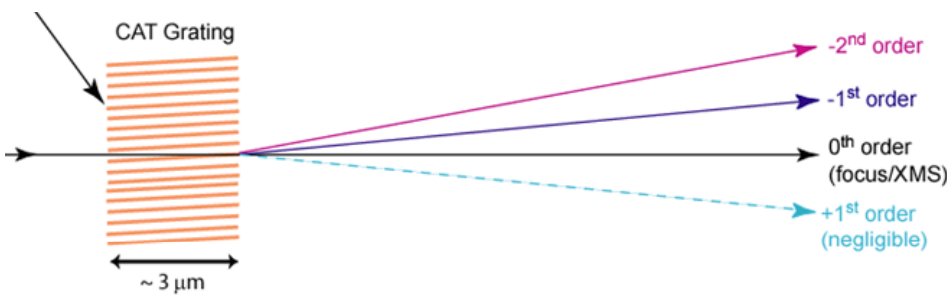
X-ray Grating Spectrometer (XGS)

- **Key Performance Requirements:**
  - Effective area >1000 cm2 from 0.3 to 1 keV
  - Spectral resolving power 3000 over full band
- **Two Grating Approaches Under Consideration**
  - Off-Plane reflection grating
  - Critical Angle Transmission Grating
- **"Critical Angle Transmission" (CAT) chosen for initial observatory study**
  - gratings mount to the aft ("exit end") of the FMA
  - Two thin grating arrays cover portion of FMA
  - Gratings have high line density (10,000 l/mm) (TBR) and are blazed:
  - Heritage from Chandra, XMM, and sounding rockets
- **CCD detector readout for the dispersed spectrum**
  - 32 CCD's in a 780 mm long array located on the fixed detector platform, 720 mm from optical axis
  - CCD's operate at -90 C to ±10 C
  - Fast readout with thin optical blocking filters
    - Readout every 0.1 seconds
  - Back-illuminated (high QE below 1 keV)
  - Heritage from Chandra, XMM, Suzaku
  - Data rate 150 kbps (ave); 1500 kbps (peak)

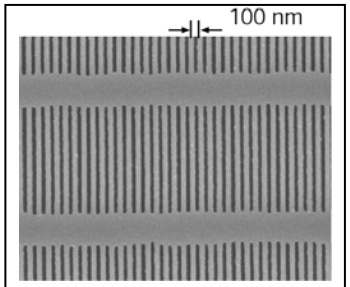


CAT (Critical-Angle Transmission) Grating Spectrometer Concept





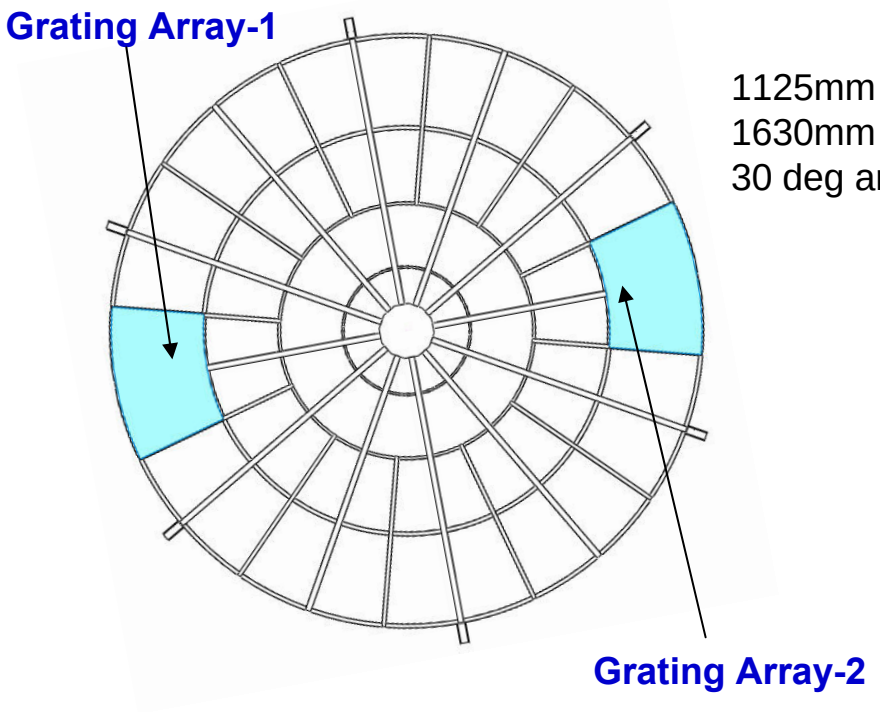
*XGS CCD camera rotated 90 deg out of page on Rowland "Sphere"



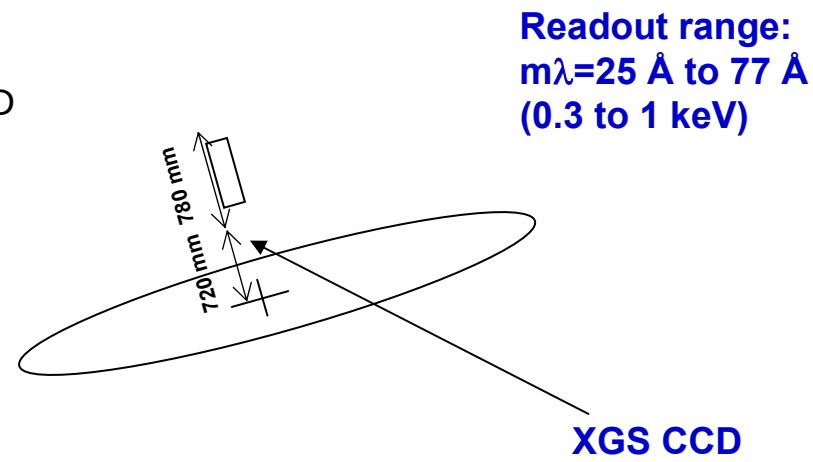
10,000 l/mm
transmission grating

CAT Grating Spectrometer Layout

- Two grating arrays mount on Flight Mirror Assembly. Both arrays use the same CCD readout.
- Each grating array covers 30 degrees of outer annulus of FMA R=1175 mm to 1600 mm. Other portions of the mirror gap are not covered to preserve throughput to the XMS, WFI and HXI.
- Readout: Covered by 32 CCD's 780 m long (including 0.4 mm gaps)



FMA



Fixed Instrument Platform

XGS Mechanical, Thermal, Power Interface Requirements

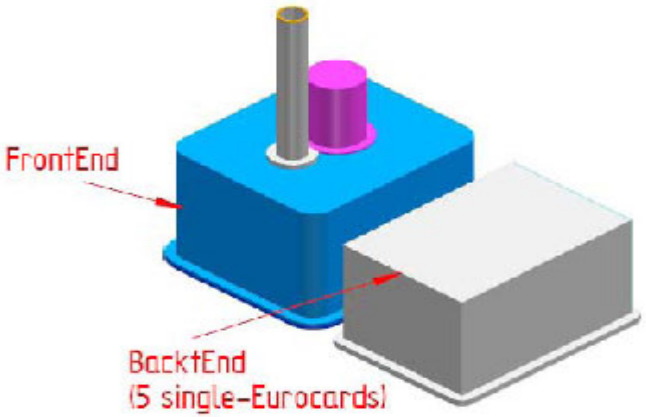
Mechanical Interface Requirements (Current Best Estimate - No Margin)					
Payload Element		Dim (cm) H x W x D	Mass (kg)	Location	Comments / Source
XGS	Grating Array -1	2x42.5x74.5	2.4	On FMA	H = 1, W and D = 2 modules
	Grating Array -2	2x42.5x74.5	2.4	On FMA	H = 1, W and D = 2 modules
	Sub-Total FMA		**4.7**		
	CCD Camera	88x24x13	26.5	On Fixed Instrument Platform	Camera only - Includes contamination door and shielding
	Detector Electronics & Mechanism Controller (DEMC)	11x11x27	6.0	< 1m from CCD Camera	Place on mirror side of FIP
	Digital Processing Assembly (DPA)	11x11x15	2.5	< 4m from CCD Camera	
	Sub-Total FIP		**35.0**		
	TOTAL XGS		**39.7**		

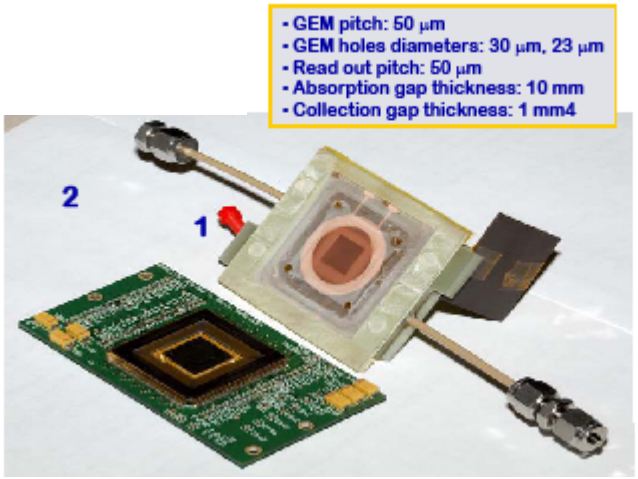
Instrument Thermal Interface Requirements					
Payload	Element	Operating	Annealing	Survival - (Off)	Comments / Source
XGS	Grating Arrays	20 +/- 1 C		18 to 53C	/ Jay email 7-18-08 for operating
	CCD Camera	-90 +/- 10C		-120 to 70C	5 W dissipation / Tom from survival
	CCD Detector	-90 +/- 10C		-120 to 70C	
	Detector Electronics Assembly (DEA)	-30 to 10C		-30 to 55C	
	Digital Processing Electronics (DPE)	-30 to 10C		-30 to 55C	
	Power Supply & Mechanism Controller	-30 to 10C		-30 to 55C	

Instrument Power Interface (Current Best Estimate - No Margin)							
Instrument	Element	Power (W)					Comments /Source
		Average	Peak	Annealing	Standby - Sleep	Safe Hold - Off	
XGS	Grating Array-1	0.0	0.0		0.0	0.0	
	Grating Array-2	0.0	0.0		0.0	0.0	
	CCD Camera	5.0	7.2		5.0		Trim heater power
	Detector Electronics & Mechanism Controller (DEMC)	50.0	50.0		10.0	0.0	
	Digital Processing Assembly (DPA)	41.3	41.3		20.0	0.0	Space cube
	Total XGS	**96.3**	**98.5**		**35.0**	**0.0**	

X-Ray Polarimeter (XPOL)

- **Key Performance Requirements**
  - **FOV = 2.6 x 2.6 arcmin**
  - **E = 2-10 keV, E/ΔE = 20% at 6 keV**
- **Features**
  - **Based on scintillating gas cell**
  - **Track detection gives polarization angle**
  - **300 x 352 pixels - 50 x 43.3 μm^2**
  - **15.24 x 15 mm^2**
  - **T_{det} = 10 C ±2 C**
  - **Room Temperature Electronics**
  - **Baffle required**
- **Interface Requirements**
  - **One detector head + FEE & back-end box on MIP**





XPOL Mechanical Interface Requirements

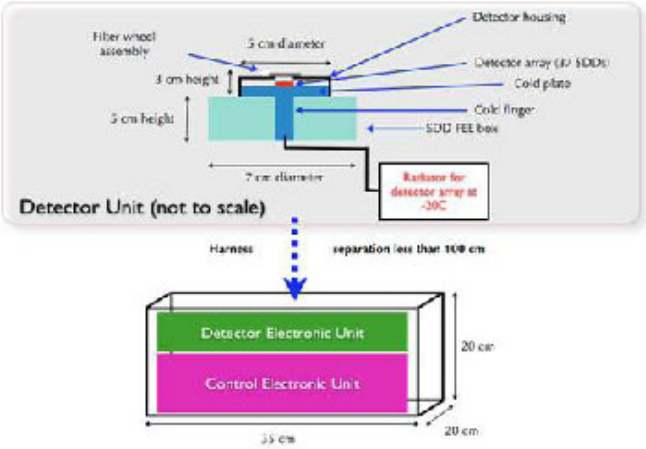
Mechanical Interface Requirements (Current Best Estimate - No Margin)					
Payload Element		Dim (cm) H x W x D	Mass (kg)	Location	Comments / Source
XPOL	Focal Plane Assembly (XPOL-FPA)	17x19x27	3.3		External baffle included
	Detector + FEE				
	Filter Wheel				
	Backend Electronics (XPOL-BBE)	19x14x11	1.6	< 20 cm (bolt together)	
	Sub-Total MIP		**4.9**		
	Control Electronics (XPOL-CE)	29x20x11	5.6		
	Sub-Total FIP		**5.6**		
	TOTAL XPOL		**10.5**		

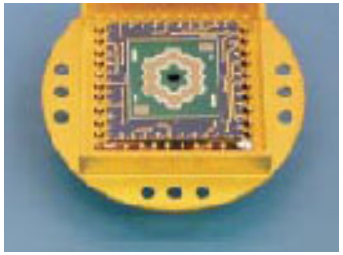
Instrument Thermal Interface Requirements					
Payload	Element	Operating	Annealing	Survival - (Off)	Comments / Source
XPOL	Focal Plane Assembly (XPOL-FPA)				
	Detector + FEE	+5 ±1 C		-15 to +45 C	Internal local heater regulator
	Filter Wheel	0C to 40C		-15 to +60 C	
	Backend Electronics (XPOL-BBE)	0C to 40C		-15 to +60 C	
	Control Electronics (XPOL-CE)	0C to 40C		-15 to +60 C	

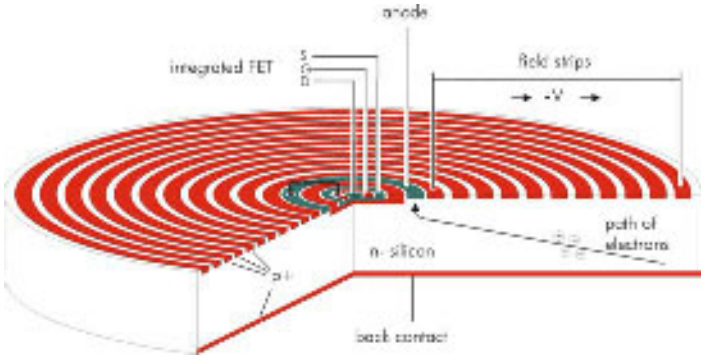
Instrument Power Interface (Current Best Estimate - No Margin)							
Instrument	Element	Power (W)					Comments /Source
		Average	Peak	Annealing	Standby - Sleep	Safe Hold - Off	
XPOL	Backend Electronics (XPOL-BBE)	8	8		0	0	
	Control Electronics (XPOL-CE)	28	28		0.0	0.0	
	TOTAL XPOL	**36**	**36**		0.0	0.0	

High Time Resolution Spectrometer (HTRS)

- **Key Performance Requirements**
  - Count Rate ~ 1 Mcps
  - Resolution = 10 μs
  - Bandpass = 0.5 – 20 keV
  - Field of View: The instrument is non-imaging. Multiple pixels are used for distributing higher count-rate capability
- **Features**
  - Based on 37 silicon drift detector diodes; placed in defocused beam (182 mm)
  - Tdet = -20 C ± 1 C
- **Interface Requirements**
  - One detector head + FEE and one electronics box on MIP
  - Baffle required – (needs to take defocusing of PSF into account)







HTRS Mechanical, Thermal, Power Interface Requirements

Mechanical Interface Requirements (Current Best Estimate - No Margin)					
Payload Element		Dim (cm) H x W x D	Mass (kg)	Location	Comments / Source
HTRS	Focal Plane Assembly (HTRS-DEU)	8x7dia	6.6		
	Detector				
	FEE+filter wheel				
	Central Electronic Unit (HTRS-CEU)	20x35x20	18.5		
	TOTAL HTRS ON MIP		**25.1**		Payload Accommodation Equipment (PAE) / P. Reid with T. Buckler mod

Instrument Thermal Interface Requirements					
		Operating	Annealing	Survival - (Off)	Comments / Source
HTRS	Focal Plane Assembly (HTRS-DEU)				
	Detector	-20 +/- 2 C		-40 to +35 C	
	FEE + Filter Wheel	0C to 40C		-40 to +35 C	
	Central Electronic Unit (HTRS-CEU)	0C to 40C		-40 to +35 C	

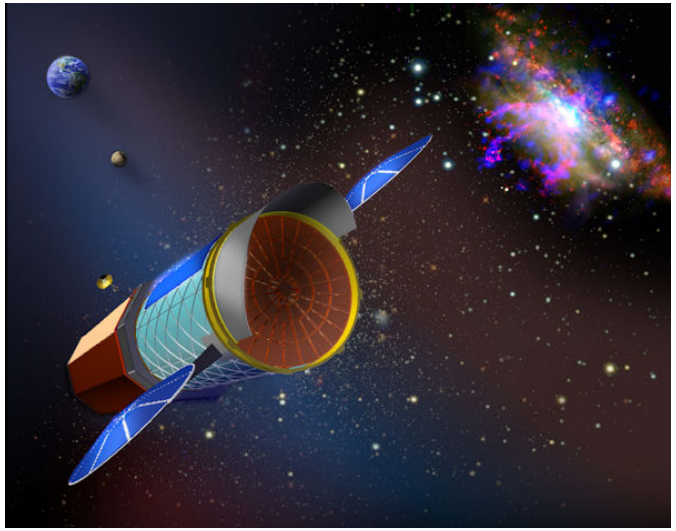
Instrument Power Interface (Current Best Estimate - No Margin)							
Instrument	Element	Power (W)					Comments /Source
		Average	Peak	Annealing	Standby - Sleep	Safe Hold - Off	
HTRS	Focal Plane Assembly (HTRS-DEU)	36	36		0.0	0	
	Detector	12	12				
	FEE + Filter Wheel	24	24				
	Central Electronic Unit (HTRS-CEU)	58.3	58.25		**0.0**	0.0	
	TOTAL HTRS	**94.3**	**94.3**		**0.0**	**0.0**	

Instrument Science / Eng Data Requirements

- **Storage, size for**
  - 48 hours including 12 hours of peak rate and 36 hours of average rate (this is called 48-hour-peak-volume)
  - AND up to 1 day of missed passes (ie., an additional 24 hrs of avg data rate)
  - FOR A TOTAL of 12 hours peak plus 60 hours of avg data
  - (Assume 100% efficiency for this 72 hour storage sizing)
- **Downlink/Latency**
  - Data collected at average rate must meet 72 hour latency requirement
  - Size to downlink 48-hour-peak-volume over period of 2 weeks above the avg rate required for data latency of 72 hours
  - Allows for 2 bright source observations (peak) per month
- **5 year mission**
  - 3% of the time at peak data rate

IXO Table Top Review

2009 03 12
NASA GSFC, Bldg 23, Room C130D



Systems Engineering

Gabe Karpati
IXO Mission Systems Engineer

OUTLINE

- Major Attributes
- Systems Engineering Process
  - Requirements Flowdown
  - Key Drivers
  - Performance Modeling
- Trades
- System Margins
- Interesting Aspects of the Observatory Configuration

IXO Major Attributes

- The IXO mission concept is exceptionally mature
  - With a decade of systems engineering work, IXO's details and refinements far exceed the customary Pre-Phase-A expectations
    - Two MDL and one IDL Studies performed directly for IXO
    - Directly traceable to three previous Con-X MDL Studies
- IXO's design is sound
  - All mission requirements were flown down from science requirements
  - Design is fully convergent:
    - the concepts for every aspect of the mission were traded, analyzed, and thoroughly engineered
    - Sufficient number of iterations was conducted across the entire System to resolve overarching interdependencies, and achieve full convergence and self-consistency
  - IXO meets or exceeds all of its performance requirements
    - Performance estimates are tracked in comprehensive error budgets
    - Performance verified with integrated FEM – 3D Thermal – Control System models
- The IXO spacecraft is feasible with technologies that exists today
  - The IXO Master Equipment List contains over 500 (TBC) entries, all having a TRL 6, or higher
  - Most components are commercially available "off-the-shelf"
- Resource Margins are good
  - All IXO resource margins meet or exceed requirements
    - Resource tracking conducted per AIAA standards and NASA guidelines
- The IXO system is robust
  - Class-B level redundancy
  - Numerous failsafe mechanisms and contingency mode operations plans
    - Such as: deployment and full mission on 2 out of 3 Masts
  - All spacecraft components and design solutions are traceable to space flight heritage

Systems Engineering Process

- Requirements Flowdown
- Key Drivers
- Performance Modeling

Astronomy Science – Observatory Payload Performance Requirements Connection

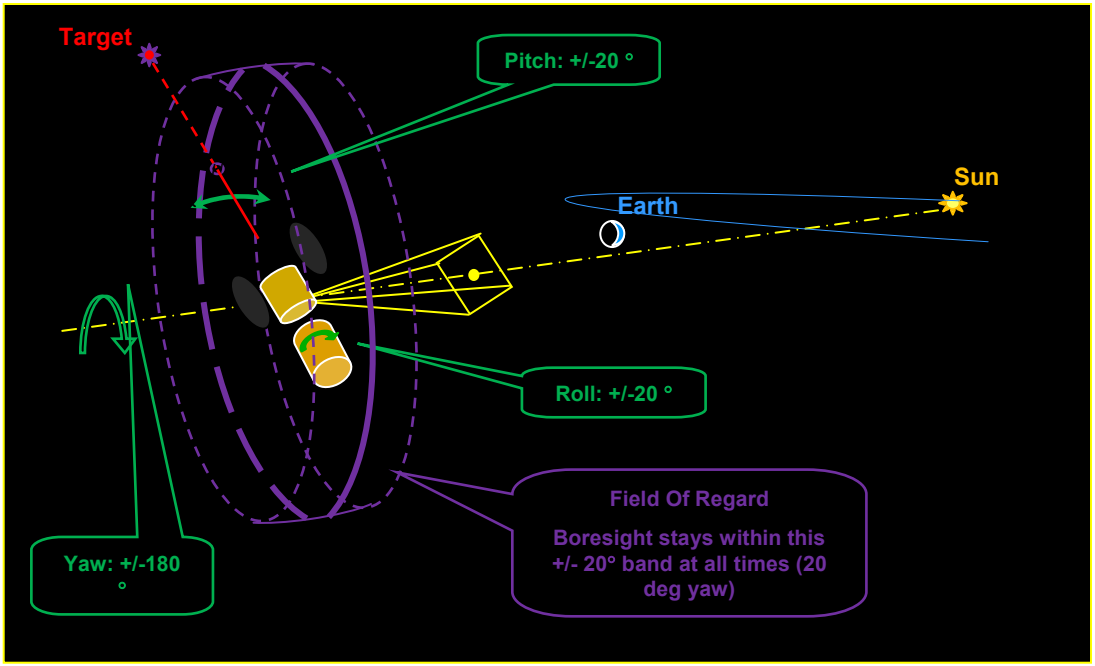
Mirror Effective Area	3 m^2 @1.25 keV 0.65 m^2 @ 6 keV 150 cm^2 @ 30 keV 1000 cm^2 (0.3 – 1 keV)	Black Hole evolution Strong gravity Strong gravity Missing Baryons
Spectral Resolution (FWHM), over FOV, over band	ΔE = 2.5 eV, 2x2', (0.3 - 7 keV) ΔE = 10 eV, 5x5', (0.3 - 7 keV) ΔE =150 eV, 18', (0.1 - 15 keV) $E/\Delta E$ = 3000, (0.3 - 1 keV) ΔE = 1 keV, 8x8', (10 – 40 keV)	Black Hole evolution Black Hole evolution Large scale structure Missing baryons Strong Gravity
Angular Resolution	≤5 arc sec HPD (0.1 – 7 keV) 30 arc sec HPD (7 - 40 keV)	Cosmic Feedback Black Hole evolution
Count Rate	1 Crab with >90% throughput. ΔE < 150 eV @ 6 keV (0.1 – 15 keV)	Strong gravity, EOS
Polarimetry	1% MDP on 1 mCrab,100 ksec, 3 σ , 2 - 6 keV	AGN geometry, strong gravity
Astrometry	1 arcsec at 3 σ confidence	Black hole evolution
Absolute Timing	50 μ sec	Neutron star studies

Science Performance Requirements

Mirror Effective Area	3 m^2 @1.25 keV 0.65 m^2 @ 6 keV 150 cm^2 @ 30 keV	Black hole evolution, large scale structure, cosmic feedback, EOS Strong gravity, EOS Cosmic acceleration, strong gravity
Spectral Resolution/FOV E = 0.3 – 7 keV E = 0.3 –1 keV	ΔE = 2.5 eV within 2 arc min 10 eV within 5 arc min < 150 eV within 18 arc min E/ΔE = 3000 from with an area of 1,000 cm^2	Black Hole evolution, Large scale structure Missing baryons using tens of AGN
Mirror Angular Resolution	≤5 arc sec HPD <7 keV ≤30 arc sec HPD > 7 keV	Large scale structure, cosmic feedback, black hole evolution, missing baryons Black hole evolution
Count Rate	1 Crab with >90% throughput	Strong gravity, EOS
Polarimetry	1% MDP on 1 mCrab in 100 ksec (2 - 6 keV)	AGN geometry, strong gravity
Astrometry	1 arcsec at 3 σ confidence	Black hole evolution
Absolute Timing	50 μ sec	Neutron star studies

Science Observations Requirements

Field of Regard	▪ Pitch: +/- 20° off Sunline ▪ Yaw: +/- 180° ▪ Roll: +/- 10° (with a goal of 20°) off Sunline
Slew	▪ Average slew: 60 degrees in 60 minutes ▪ Average # of slews per day: 2.5 during first year of mission, less later
Operational Efficiency	▪ 85% average over the mission life
Timing accuracy	▪ Photon arrival tagged to UTC to ±100 μsec



Five Instruments

- On-axis (on Movable Instrument Platform): XMS, WFI/HXI, HTRS, X-Pol
- Off axis (on Fixed Instrument: Platform): XGS

Four Science Modes

- One Science Mode for each MIP instrument
- XGS operates during all Science Modes
- Instruments that are not conducting science are in Standby

		Science Modes			
		Mode 1	Mode 2	Mode 3	Mode 4
Instrument Operations	Science	XMS, XGS	WFI/HXI, XGS	X-Pol, XGS	HTRS, XGS
	Standby	WFI/HXI, X-Pol, HTRS	XMS, X-Pol, HTRS	WFI/HXI, HTRS, XMS	WFI/HXI, XMS, X-Pol
% time		40%	40%	10%	10%
Observation Duration	Average	10 hours			
	Minimum	30 minutes			
	Peak	48 hours			

Science Requirements Flowdown to Top Mission Systems Requirements

- **Image Quality Requirements** *>>> Pointing Control >>> GN&C, Structure, Mechanisms*
- **Image Positioning Requirements** *>>> Pointing Control*
- **Aspect Knowledge Requirements** *>>> Pointing Knowledge >>> TADS*
- **Science Observations Environment Requirements** *>>> L2 Orbit*
- **Mission Resource Constraints** *>>> LV Requirements*
  - **Fairing** *>>> Deployable Metering Structure*
  - **Throw Mass** *>>> Key Trades Attribute*
  - **Launch Dynamics** *>>> Natural Frequencies >>> Structure, Control System*
- **L2 Orbit Determination Requirements** *>>> Stationkeeping >>> Solar Momentum Management >>> Prop and GN&C >>> CP/CM offset*
- **L2 Environment (Micrometeorite Threat , Constant sun, Differential charging, etc.)** *>>> Shroud, Thermal, EPS*
- **Science Payload Complement (i.e. Instruments)** *>>> Moveable Platform*
- **Science Products Requirements** *>>> Con Ops*
- **Mission Life** *>>> Consumables sizing, Reliability, etc.*
- **Mission Success Requirements** *>>> Failure tolerance, Reliability*
- **Science Data Volume** *>>> C&DH, RF Comm*

Requirements Flowdown Example
from XMS Instrument Image Quality Error Budget

P. B. Reid
Harvard-Smithsonian Center for Astrophysics
May 27, 2008

	Micro-calorimeter Spatial Resolution Goals Error Budget - Mission(1 SXT, single Atlas V Launch)										
	ITEM (HPD - arcsec)	RQMT	Margin		Allocation						RATIONALE
1	Calorimeter 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
4	Telescope level effects				1.51						RSS
5	Image Reconstruction errors (over obs)					1.41					RSS
1 → 6	Attitude knowledge drift						1.00				Chandra experience
7	FMA/XMS focal plane drift (thermal)						1.00				Chandra experience - includes FID light system
2 → 8	FMA/XMS vibration effects					0.20					Chandra experience (jitter)
3 → 9	FMA/XMS misalignment (off-axis error)					0.05					field dependent aberration =+/- 30 arc-sec alignment
4 → 10	FMA/XMS 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				
21	Module to Module alignment						1.00				
22	Module						3.76				
23	Distort. & misalign due to module packing							0.71			
24	Mirror Pair Co-alignment							0.71			
25	Mirror Pair							3.63			RSS
26	P-S alignment in module(using CDA)								1.12		RSS
27	CDA Dynamic Accuracy									0.50	
28	CDA Static Static Accuracy									0.50	
29	Thermal Drift									0.50	
30	Focus and Coma Alignment									0.71	
31	Reflector Installation in module								1.00		
32	Reflector Pair (P-S)								3.30		Est based on tech dev program to date
	Color Code	Rqmt		Margin		RSS Predict			Allocation		

Derived key Observatory Pointing Requirements

1. **Attitude Knowledge:** 1.0 as [HPD]
2. **Jitter:** +/- 0 2 arcsec = +/- 0.02 mm in X and Y
3. **Max. X/Y displacement** (for Imaging only!) : +/- 30 arcsec = +/- 3 mm in X and Y
4. **Defocus:** +/- 0.5 arcsec => +/- 0.3 mm in Z (assuming a conservative f(6) beam)

Note: at 20m focal length 10 as =~ 1 mm

Error Budget Example

Observatory Level Pointing Knowledge Budget - Top Layer

Image Reconstruction Boresight Pointing Radial Knowledge

Radial Requirement	Expected Performance
1 arcsec radial [HPD]	.54 arcsec [HPD]

RSS

Boresight Offset Knowledge Error
(i. e. TADS error)

Sub-allocated Requirement	Expected Performance
.8 arcsec radial [HPD]	.45 arcsec radial [HPD]

Star Tracker Attitude Knowledge Error

Sub-allocated Requirement	Expected Performance*
.5 arcsec radial [HPD]	.3 arcsec radial [HPD]

** After in flight optical distortion calibrations*

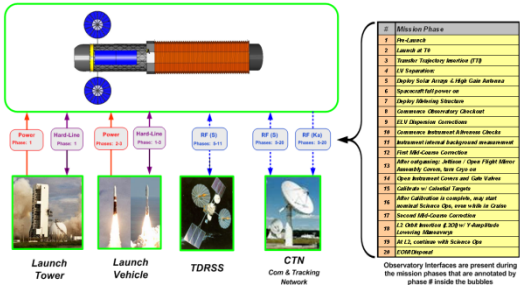
Jitter
(outside of TADS bandwidth)

Sub-allocated Requirement	Predicted Performance
.15 arcsec radial [HPD]	.02 arcsec radial [HPD]

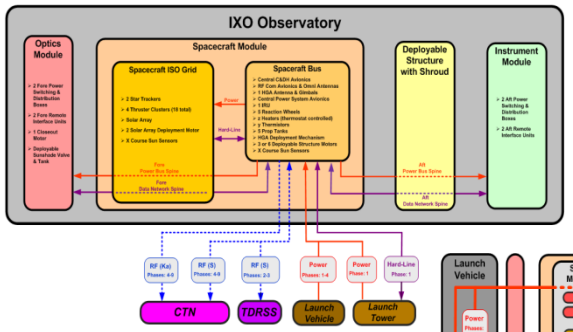
The Requirement for Roll Knowledge is:
- 3 arcsec [HPD]

The Expected Performance for Roll Knowledge is:
- 2 arcsec [HPD] (stability over a science observation)

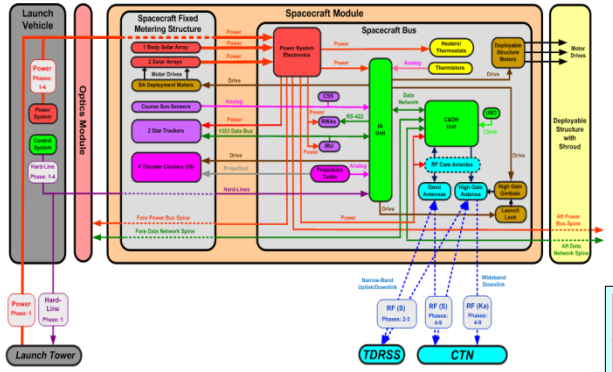
Systematic System Architecture Concept Development; Architectural Level Definitions



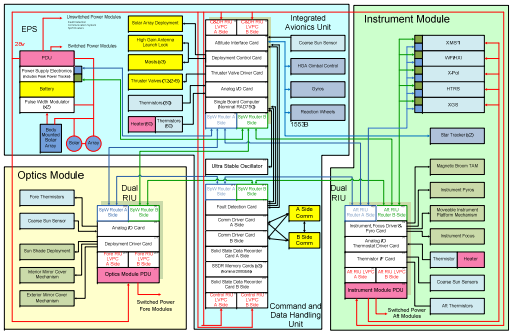
Level-1: Mission / Observatory



Level-2: Module Functions



Level-3: Subsystems



Present IXO development effort conducted mostly at Level 4 → **Level-4: Sub-Assemblies**

Systems Engineering Tools: Multilevel Integrated Modeling

- First Level of Observatory modeling: highly cross-linked Systems Spreadsheet
  - Principal design tool for quick response decisions
  - Dozens of WorkSheets - the "Origin" is the MEL (organized per WBS breakdown with Module level then Spacial sub-ordering)
  - Recursive cross-links to various mass reports; feed and get fed from: propellant, CG, CP, and momentum calculators, etc.
- Second Level of Observatory modeling: 3D Mechanical design (IDEAS) – novel approach: Observatory configuration published as a 3D .pdf model
  - For all to examine, rotate, zoom-in, see thru… …understand the Observatory
  - Some models / mockups actually physically built (folded Deployable Shroud)
- Third Level of Observatory modeling: Advanced Numeric Models
  - 3D Thermal Model
  - FEM and Jitter simulations
  - Control System model and simulations
- Fourth Level of Observatory modeling: Integrated Models
  - Various integrations for various analyses of the Thermal/FEM/ Control System Models

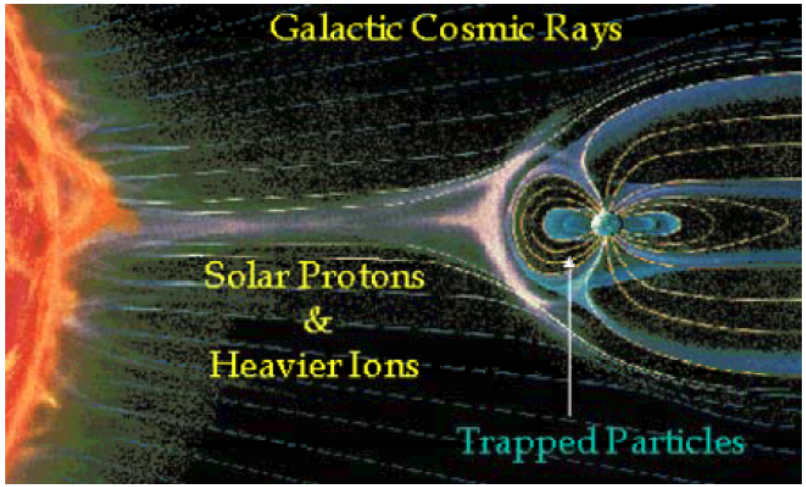
Controlling Systems Engineering Documents

- Process for the Systems Engineering of Goddard Space Flight Center (GSFC) Missions
  - GPR-7120.5A_.pdf
- NASA Systems Engineering Handbook
  - NASA-SP-2007-6105-Rev-1-Final-31Dec2007.pdf
- Mass Properties Control for Space Systems
  - AIAA_S-120-2006_MassPropertiesControl.pdf
- Goddard Space Flight Center Gold Rules
  - GSFC-STD-1000.pdf
- Risk Classification for NASA Payloads
  - NPR_8705_0004_.pdf
- Space Mission Analysis and Design
  - Wertz / Larson, Third Edition, 1999

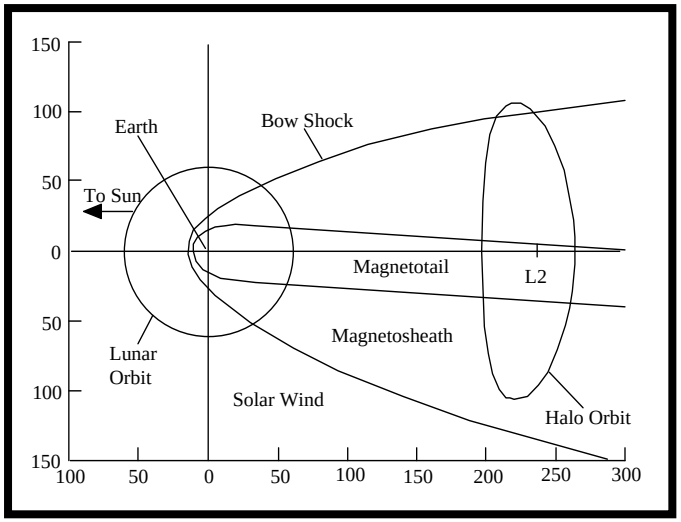
Trades

Major Trades

- Orbit type
  - BASELINE: L2
  - TRADED: LEO, GEO, Driftaway
    - The quiet L2 environment is an easy winner (like JWST)

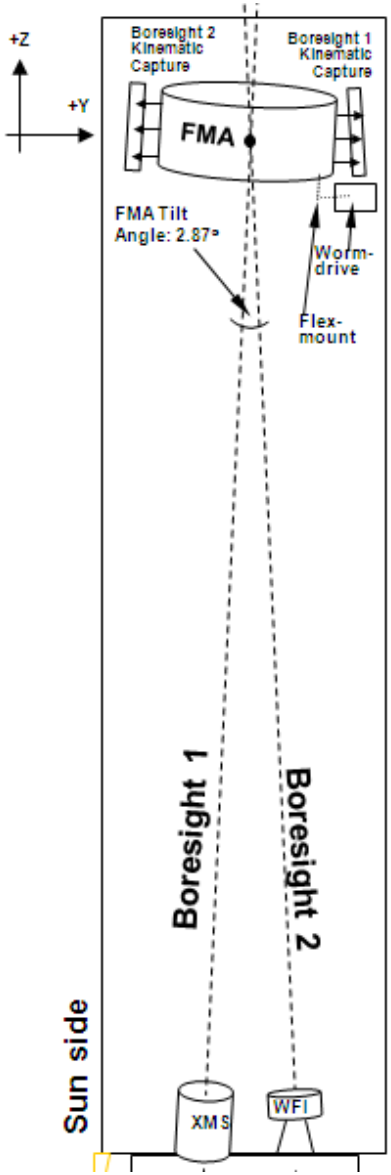


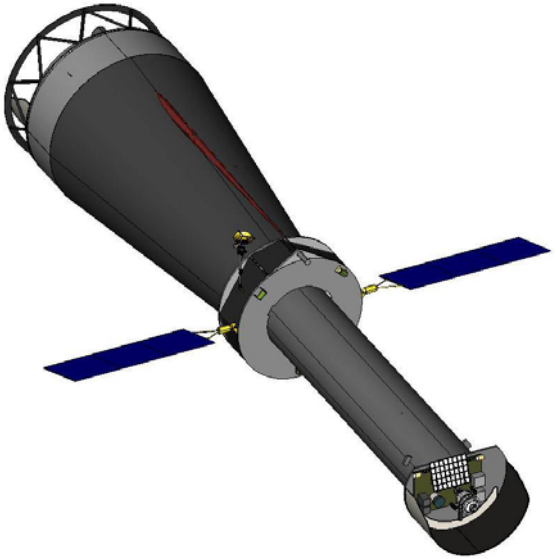
- Orbit amplitude
  - BASELINE: 800,000 km (zero delta-v)
  - TRADED: lower to 700,000 km (using propellant)
    - An early concern regarding the accumulation of solar particle right at Magnetosheath
    - Based on the work of one scientist; no one could reproduce his results; structure of particle distribution at Magnetosheath is not known to +/- 100.000 km

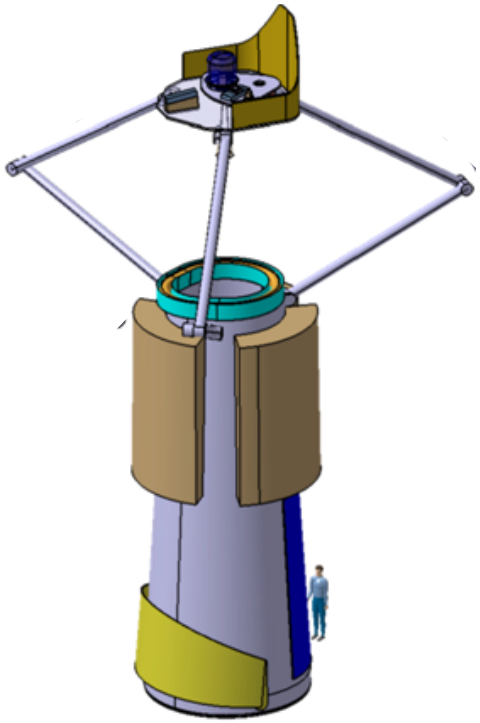


Major Trades

- Metering Structure deployment method
  - BASELINE: ADAM masts
    - Lightweight
    - Excellent mechanical properties
    - Reliable
  - TRADED:
    - Spyglass, Drinking cups and various Telescoping Deployments
    - Tilt FMA
    - Umbrella-like arms (ESA)
    - "Snap-dragon" fold in half like a pocket –knife (ESA)



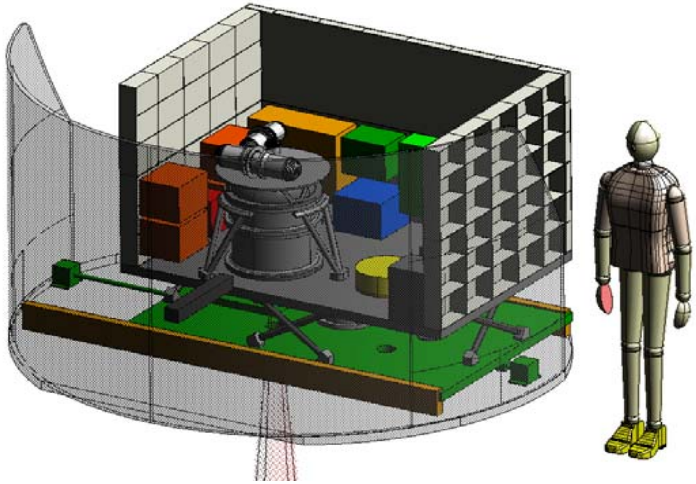




Major Trades

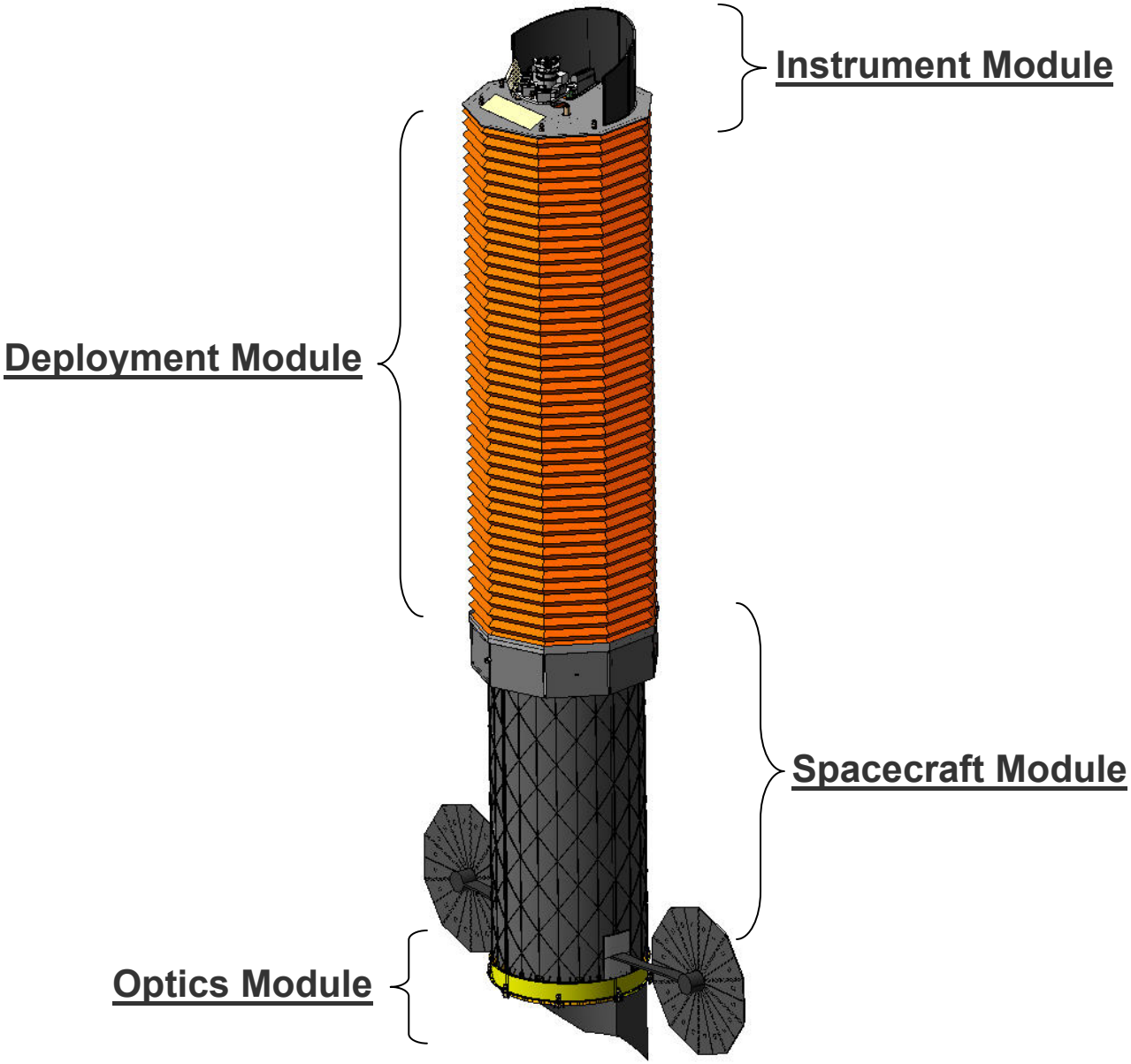
- Number of Masts
  - BASELINE: 3
  - TRADED: 4
    - Mass is the deal breaker

- Moveable Instrument Platform approaches
  - BASELINE: pivot
  - TRADED: slide – harness long (w/ service loop), hard to imlement



- Solar Torque offloading methods
  - BASELINE: .9N monoprop (same as Voyager)
  - TRADED: Solar Sail, electrical propulsion, construction tricks
    - Baseline is by far the lightest, simplest, precise-est, great Voyager heritage (> 500,000 successful firings)

Consolidated "Baseline" Design



System Resources and Margins

Information Sources

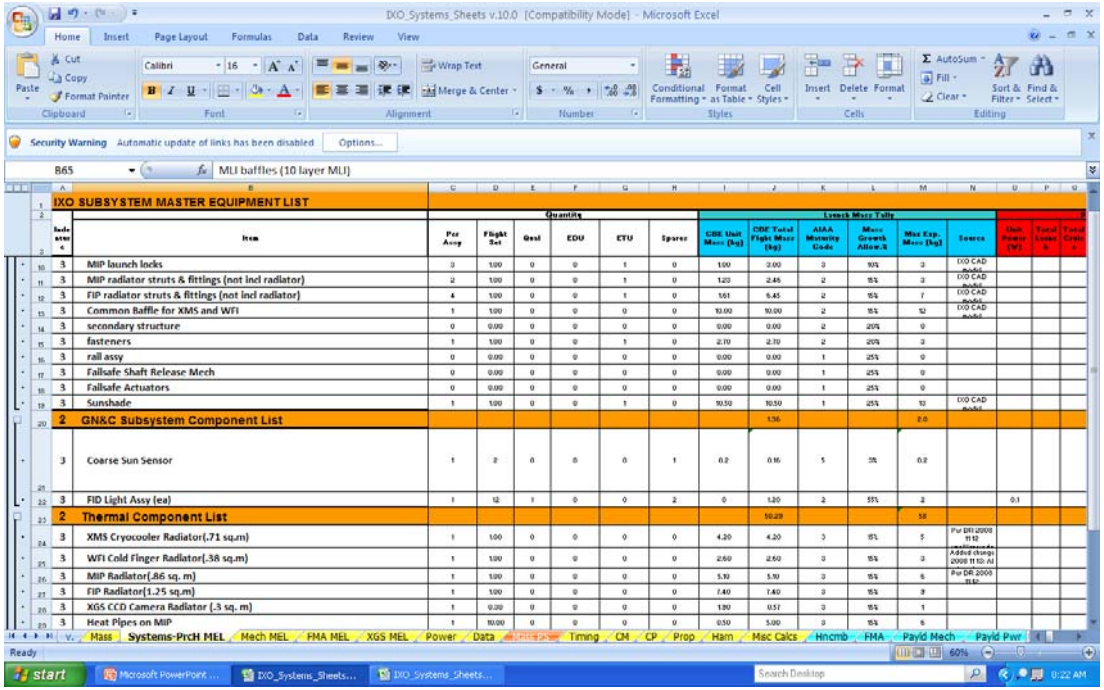
- Mission Design Lab reports
  - Propulsion
  - Avionics
  - Thermal
  - RF Communication
  - G,N &C…
- CAD Mechanical layouts
- Instrument and Mirror Teams
- Lockheed Analysis and Integrated Modeling
- Systems Engineering Calculations
  - Power and Data Harnesses
  - Solar array sizing…

Integrated Resource Spreadsheet

- Provides running totals for mass, power and data
- Includes Detailed component information gathered into Master Equipment lists(MELs)
  - Part dimensions, heritage, grass roots cost estimate, data source, TRL, pictures…..

•Changes to component information immediately reflected in

- •Mass total by Spacecraft module or Subsystem
- •Required propellant for given launch mass
- •Spacecraft Center of Mass
- •Average Mass Growth Allowance (contingency) by subsystem
- •Margin with respect to Atlas 5 launch vehicle



IXO SUBSYSTEM MASTER EQUIPMENT LIST

Index	Item	Quantity: Per Assy	Flight Set	Qual	EDU	ETU	Spares	CBE Unit Mass (kg)	CBE Total Flight Mass (kg)	AIAA Maturity Code	Mass Growth Allow. %	Max Exp. Mass (kg)	Source	Unit Power (W)	Total Load	Total Cost
3	MIP launch locks	3	1.00	0	0	1	0	1.00	2.00	3	10%	3	IXO CAD model			
3	MIP radiator struts & fittings (not incl radiator)	2	1.00	0	0	1	0	1.23	2.46	2	15%	3	IXO CAD model			
3	FIP radiator struts & fittings (not incl radiator)	4	1.00	0	0	1	0	1.61	6.45	2	15%	7	IXO CAD model			
3	Common Baffle for XMS and WFI	1	1.00	0	0	0	0	10.00	10.00	2	15%	12	IXO CAD model			
3	secondary structure	0	0.00	0	0	0	0	0.00	0.00	2	20%	0				
3	fasteners	1	1.00	0	0	1	0	2.70	2.70	2	20%	3				
3	rail assy	0	0.00	0	0	0	0	0.00	0.00	1	25%	0				
3	Failsafe Shaft Release Mech	0	0.00	0	0	0	0	0.00	0.00	1	25%	0				
3	Failsafe Actuators	0	0.00	0	0	0	0	0.00	0.00	1	25%	0				
3	Sunshade	1	1.00	0	0	1	0	10.50	10.50	1	25%	13	IXO CAD model			
2	GN&C Subsystem Component List								1.56			2.0				
3	Coarse Sun Sensor	1	2	0	0	0	1	0.2	0.16	5	5%	0.2				
3	FID Light Assy (ea)	1	12	1	0	0	2	0	1.20	2	55%	2		0.1		
2	Thermal Component List								10.29			18				
3	XMS Cryocooler Radiator(.71 sq.m)	1	1.00	0	0	0	0	4.20	4.20	3	15%	5	Per DR 2009 11.12			
3	WFI Cold Finger Radiator(.38 sq.m)	1	1.00	0	0	0	0	2.60	2.60	3	15%	3	IXO CAD model Added change 2009 11.12: AJ			
3	MIP Radiator(.86 sq. m)	1	1.00	0	0	0	0	5.10	5.10	3	15%	6	Per DR 2009 11.12			
3	FIP Radiator(1.25 sq.m)	1	1.00	0	0	0	0	7.40	7.40	3	15%	8				
3	XGS CCD Camera Radiator (.3 sq. m)	1	0.30	0	0	0	0	1.30	0.51	3	15%	1				
3	Heat Pipes on MIP	1	10.00	0	0	0	0	0.50	5.00	3	15%	6				

Observatory Level Mass Margin Assessment

- **Mass estimation process per w/ AIAA S-120**
  - **Variable "Max Growth Allowance [MGA]" contingency %'s assigned to each MEL line item**
  - **MGA %'s are specified in the Standard as a function of 1.) maturity, and 2.) equipment type (i.e. battery, electronics, structure, etc.)**

Table 1 — Mass Growth Allowance and Depletion Schedule

Major Category	Maturity Code	Design Maturity (Basis for Mass Determination)	Mass Growth Allowance (%)												
			Electrical/Electronic Components			Structure	Brackets, Clips, Hardware	Battery	Solar Array	Thermal Control	Mechanisms	Propulsion	Wire Harness	Instrumentation	ECLSS, Crew Systems
			0-5 kg	5-15 kg	>15 kg										
E	1	**Estimated** 1) an approximation based on rough sketches, parametric analysis, or undefined requirements, 2) a guess based on experience, 3) a value with unknown basis or pedigree.	30	25	20	25	30	25	30	25	25	25	55	55	23
	2	**Layout** 1) a calculation or approximation based on conceptual designs (equivalent to layout drawings), 2) major modifications to existing hardware	25	20	15	15	20	15	20	20	15	15	30	30	15
C	3	**Preliminary Design** 1) calculations based on a new design after initial sizing but prior to final structural or thermal analysis, 2) minor modification of existing hardware	20	15	10	10	15	10	10	15	10	10	25	25	10
	4	**Released Design** 1) calculations based on a design after final signoff and release for procurement or production, 2) very minor modification of existing hardware, 3) catalog value	10	5	5	5	6	5	5	5	5	5	10	10	6
A	5	**Existing Hardware** 1) actual mass from another program, assuming that hardware will satisfy the requirements of the current program with no changes, 2) values based on measured masses of qualification hardware	3	3	3	3	3	3	3	2	3	3	5	5	4
	6	**Actual Mass** measured hardware	No mass growth allowance – use appropriate measurement uncertainty values												
	7	**Customer Furnished Equipment or Specification Value**	Typically a "not-to-exceed" value is provided; however, contractor has the option to include MGA if justified												

Observatory Level Mass Summary and Margin Analysis

Mirrors	Estimate	Avg. MGA	Max. Exp. Mass
Flight Mirror Assembly	1748	17%	2037
Mirrors Total	**1748**		**2037**

Payload	Estimate	Avg. MGA	Max. Exp. Mass
X-ray Microcalorimeter Spectrometer	257	30%	334
Wide Field Imager	75	30%	97
X-ray Grating Spectrometer	41	30%	53
HXI	24	30%	31
XPOL	11	30%	14
HTRS	25	30%	33
Payload Accommodations	148	22%	181
Payload Total	**579**		**742**

Subsystems	Estimate	Avg. MGA	Max. Exp. Mass
Avionics	80	15%	92
Communications	28	4%	29
Attitude Control	107	6%	113
Structure and Mechanisms	1144	14%	1308
Power	118	8%	128
Propulsion (dry)	80	7%	85
Thermal	158	18%	187
Harness	273	30%	355
Subsystems Total	**1987**		**2297**

Observatory	Estimate	Avg. MGA	Max. Exp. Mass
Science Payload Total	2327	19%	2779
Bus Total	1987	16%	2297
Observatory On Orbit Dry Mass	4314	18%	5076
Separation System LV Side	272	6%	290
Observatory Launched Dry Mass	**4586**	**17.0%**	**5366**
Propellant Mass (10 yrs)			197
Observatory Wet Launch Mass			**5563**

Margin	
Atlas V 551 Throw Mass (C3=-0.5)	**6425**
Margin (above Max. Exp. WL Mass) [kg]	**862**
Margin (above Max. Exp. WL Mass) [%]	**15.5%**
Composite Overall Mass Growth Allowance [%]	**17.0%**
Margin plus Mass Growth Allowance [%]	**32.5%**

PROJECT REQUIREMENT

Total Launch Mass Margin (The sum of the "composite" Mass Growth Allowance %, and the Project Reserve Margin %)

> = 30%

Module Level Mass Summary

Item	CBE [kg]	Composite Mass Growth Allow. [%]	Max Expected Mass [kg]
Instrument Module (IM)	737	25.7%	926
XMS	257	30.0%	334
XGS IM (Camera)	35	30.0%	46
WFI	75	30.0%	97
HXI	24	30.0%	31
XPOL	11	30.0%	14
HTRS	25	30.0%	33
Payload Accommodation IM	44	25.0%	55
GN&C IM	1	48.9%	2
Avionics IM	18	15.0%	21
Mech IM	140	15.0%	161
Harness IM	59	30.0%	76
Therm IM	50	15.1%	58
Deployment Module (DM)	448	16.9%	523
Mech DM	325	12.2%	365
Harness DM	118	30.0%	154
Therm DM	4	15.0%	5
S/C Module (SCM)	1094	14.4%	1252
GN&C SCM	81	3.0%	83
Mech SCM	579	15.6%	669
Propulsion Hardware SCM	80	6.8%	85
Therm SCM	74	20.0%	89
Power SCM	118	8.3%	128
Harness SCM	92	30.0%	120
RF Comm SCM	28	4.3%	29
Avionics SCM	42	15.0%	48
Optics Module (OM)	2034	16.7%	2374
FMA (w/ HXT)	1748	16.6%	2037
XGS OM (Gratings)	6	30.0%	7
Payload Accommodation OM	104	21.3%	126
GN&C OM	25	14.0%	28
Avionics OM	20	15.0%	23
Mech OM	100	13.4%	113
Harness OM	4	30.0%	5
Therm OM	30	20.0%	36
PAF and Separation System - LV Side	272	6.5%	290
OBSERVATORY DRY LAUNCH MASS	4585	17.0%	5366
Propellant Mass (10 Years, .8Mkm)	*167*		197
OBSERVATORY WET LAUNCH MASS	*4752*		5563
Atlas V 551 Med Fairing Contractual Throw Mass (excl. PAF & Sep System)			6425
Project Margin [kg]			862
Project Margin [%]			15.5%

Observatory Level Power Loads (incl. 30% Max. Growth Allowance)

IXO Power

Max. Exp. Value (CBE + 30%)	Launch	Cruise	Science	Downlink	Slew	Safehold	Max
Observatory	**144**	**3580**	**3608**	**3640**	**2833**	**2606**	**4724**
S/C	144	633	661	694	1035	781	1467
Payload	0	2946	2946	2946	2946	1825	3257

S/C *Max. Exp. Values (CBE +30%)*

	Launch	Cruise	Science	Downlink	Slew	Safehold	Max
S/C Total	**144**	**633**	**661**	**694**	**1035**	**781**	**1467**
ACS	16	65	70	70	433	57	569
C&DH	98	192	192	203	205	185	229
RF Comm	26	57	57	104	57	57	117
Mech	0	0	0	0	0	0	0
Propulsion	0	7	7	7	13	7	7
Power	5	185	217	219	210	175	305
Harness	0	23	27	27	26	22	38
Thermal	0	104	91	65	91	279	203

Payload *Max. Exp. Values (CBE +30%)*

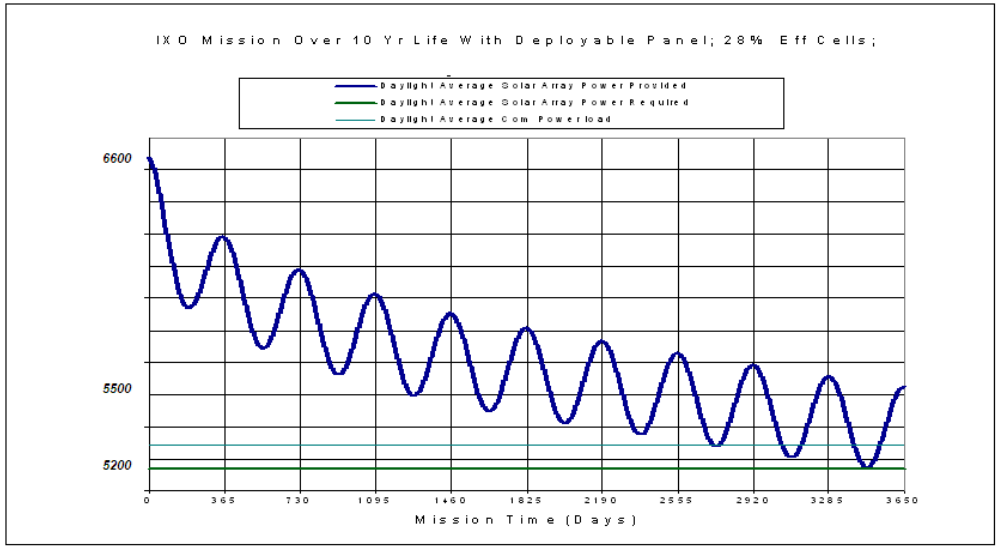
	Mode 1	Mode 2	Mode 3	Mode 3	Max
Payload Total	**2946**	**2833**	**2570**	**2646**	**3257**
FMA	2002	2002	2002	2002	2002
XMS	844	420	420	420	844
WFI	33	303	33	33	303
HXI	6	47	6	7	47
XGS	62	62	62	62	62
XPOL	0	0	47	0	0
HTRS	0	0	0	123	0

Unit Powers *Max. Exp. Values (CBE +30%)*

Ave	Standby	Safehold	Peak
3427	**2284**	**1825**	
2002	18`25	1825	1825
844	420	0	914
303	33	0	303
47	6	0	85
62	0	0	68
47	0	0	47
123	0	0	123

Observatory Level Power Margin Assessment

- Observatory Max Power Load: 4724 W
- Power System Max Output (BOL): 6600 W
  - 40% margin on top of 30% contingency over abs max load at BOL
- Power System Absolute Minimum Output (EOL, 10 yrs): 5200 W
  - 18% margin on top of 30% contingency over max science mode load at EOL
  - 10% margin on top of 30% contingency over abs max load at EOL
- Power is not a problem for IXO at L2
  - IXO is actually <u>depopulating (!)</u> solar cells from the 3.4 m dia Ultraflex arrays, flown to balance solar pressure
  - If needed, more solar cells can be added to the existing Ultraflex panels at < 0.5 kg / 100W



Observatory Level Data Generation and Storage Summary

Element		CBE Data Rates (kbps) (w/o contingency)		
		Average	Peak	Comments
FMA	Science	0.0		
	Housekeeping	1.0	1.0	
	Total FMA	**1.0**	**1.0**	
XMS	Science	25.6	1,680.0	
	Housekeeping	4.0	4.0	
	Total XMS	**29.6**	**1,684.0**	
WFI	Science	45.0	1,000.0	4.5 Mbps for high
	Housekeeping	0.2	0.2	
	Total WFI	**45.2**	**1,000.2**	
HXI	Science	10.0	1,000.0	based on BEPAC HXT
	Housekeeping	0.8	0.8	
	Total HXI	**10.8**	**1,000.8**	
XGS	Science	150.0	1,500.0	
	Housekeeping	1.0	1.0	
	Total XGS	**151.0**	**1,501.0**	
X-POL	Science	300.0	1,000.0	
	Housekeeping	0.2	0.2	
	Total X-POL	**300.2**	**1,000.2**	
HTRS	Science	50.0	50.0	
	Housekeeping	0.2	0.2	
	Total HTRS	**50.2**	**50.2**	
Total by Mode	**Mode 1**	**181.6**	**3,186.0**	
	Mode 2	**208.0**	**3,503.0**	
	Mode 3	**452.2**	**2,502.2**	
	Mode 4	**202.2**	**1,552.2**	

Weighted "daily average"	**221.3**	**<<< size RF System to this**

STORAGE MODE 1 (w/o contingency)	Rate	Unit
Low Science Data Rate per sec	181.6	kbps
Low Science Data Rate - Data Volume per hour	0.7	Gbit
Low Science Data Rate - Data Volume per day	15.7	Gbit
Low Science Data Rate - Data Volume per 60 hours	39.2	Gbit
High Science Data Rate per sec	3,186.0	kbps
High Science Data Rate - Data Volume per hour	11.5	Gbit
High Science Data Rate - Data Volume per 12 hours	137.6	Gbit
S/C Hskp Data Volume (at 4 kpbs) per day	0.3	Gbit
Mode 1 Storage Total	**177.2**	**Gbit**

STORAGE MODE 2 (w/o contingency)	Rate	Unit
Low Science Data Rate per sec	208.0	kbps
Low Science Data Rate - Data Volume per hour	748.8	Gbit
Low Science Data Rate - Data Volume per day	18.0	Gbit
Low Science Data Rate - Data Volume per 60 hours	44.9	Gbit
High Science Data Rate per sec	3,503.0	kbps
High Science Data Rate - Data Volume per hour	12.6	Gbit
High Science Data rate 12 hours	151.3	Gbit
S/C Hskp Data Volume (at 4 kpbs) per day	0.3	Gbit
Mode 2 Total	**196.6**	**Gbit**

STORAGE MODE 3 (w/o contingency)	Rate	Unit
Low Science Data Rate per sec	452.2	kbps
Low Science Data Rate - Data Volume per hour	1,627.9	Gbit
Low Science Data Rate - Data Volume per day	39.1	Gbit
Low Science Data Rate - Data Volume per 60 hours	97.7	Gbit
High Science Data Rate per sec	2,502.2	kbps
High Science Data Rate - Data Volume per hour	9.0	Gbit
High Science Data rate 12 hours	108.1	Gbit
S/C Hskp Data Volume (at 4 kpbs) per day	0.3	Gbit
Mode 3 Total	**206.1**	**Gbit**

STORAGE MODE 4 (w/o contingency)	Rate	Unit
Low Science Data Rate per sec	202.2	kbps
Low Science Data Rate - Data Volume per hour	727.9	Gbit
Low Science Data Rate - Data Volume per day	17.5	Gbit
Low Science Data Rate - Data Volume per 60 hours	43.7	Gbit
High Science Data Rate per sec	1,552.2	kbps
High Science Data Rate - Data Volume per hour	5.6	Gbit
High Science Data rate 12 hours	67.1	Gbit
S/C Hskp Data Volume (at 4 kpbs) per day	0.3	Gbit
Mode 4 Total	**111.1**	**Gbit**

Observatory Level Data Storage Margin Assessment

- Observatory Data Storage volume: 400 Gbits

- Observatory max nominal 60 hr data volume ("Low Data Rate Mode" for 60 hrs) : 100 Gbits (CBE)
  - 400% margin (on CBE)

- Observatory abs max 60 hr data volume ("Hi Data Rate Mode" for 12 hours plus "Low Data Rate Mode" for 48 hours) : 200 Gbits (CBE)
  - 200% margin (on CBE)

Observatory Level Downlink Summary

Downlink	Rate	Unit
"Low Science Data Rate" - Data Volume per day	19.1	Gbit
Instr. Hskp (incl. in Sci. Data Rate)	0.0	Gbit
S/C Hskp Data Volume (at 4 kpbs) per day	0.3	Gbit
Contingency 30%	5.8	Gbit
Reed Solomon Overhead 15%	3.8	Gbit
Total Downlinked "Low Science Data Rate" Volume per day	**29.1**	**Gbit**
Actual downlink rate to DSN 34 m w/ 70 cm HGA	26.0	Mbps
Actual "Regular" Downlink Time	**18.7**	**min**

"Low Data Rate Mode"

Downlink	Rate	Unit
"High Science Data Rate" - Data Volume per 12 hours	151.3	Gbit
Instr. Hskp (incl. in Sci. Data Rate	0.0	Gbit
S/C Hskp Data Volume (at 4 kpbs) per day	0.3	Gbit
Contingency 30%	45.4	Gbit
Reed Solomon Overhead 15%	29.6	Gbit
Total Downlinked "High Science Data Rate" Volume on "worst" day	**226.6**	**Gbit**
Actual downlink rate to DSN 34 m w/ 70 cm HGA	26.0	Mbps
Actual "Regular" Downlink Time	*145.3*	*min*

Observatory Level Downlink Volume Margin Assessment

- **Nominal daily downlink volume** (w/ nominal 30 minutes DSN contact at 26 Mbps): **50 Gbits / day**

- **Observatory max nominal downlink volume per 24 hours** ("Low Data Rate Mode" for 24 hours) : **30 Gbits / day** (Max Expected Value, incl. 30% MGA)
  - **40% margin (on top of 30% contingency)**

- **Observatory abs max downlink volume per 24 hours** ("Hi Data Rate Mode" for 12 hours plus "Low Data Rate Mode" data volume for 12 hours) : **200 Gbits** (Max Expected Value, incl. 30% MGA)
  - **Downlink by either: increasing DSN contact time to 2.5 hours once a month during the "Hi Data Rate Mode" period**
    - **Feasible, pay DSN per minute w/ 30 minutes min. charge**
  - **Or: store extra data volume (have storage space) and "drain away" extra data over several subsequent daily 30 min DSN contacts**

CPU / Flight Software Margins Assessment

Resource	Amount Available	Current Estimate	Current Margin	GOLD Rule Required Margin @Phase A
CPU (BAE750)	100%	29.10%	71%	50%
uP RAM(kB)	32768	6471	80%	50%

For this chart, Margin = (Available – Estimate) / Available

Observatory Level Pointing Margins Assessment

Term	Requirement	Predicted Performance	Margin
Image Position Reconstruction Knowledge	• **Radial: 1 arcsec (HPD)** **(that is Pitch and Yaw combined, equivalent to ~0.7" pitch and ~0.7" roll)**	• **Radial: .54 arcsec (HPD)**	**85%**
Image Position Control	• **Pitch and Yaw: 10 arcsec (3σ)**	▪ **Pitch and Yaw: 1.54 arcsec (3σ)**	**550%**
Defocus	• **+/- 0.3 m (3σ)**	▪ **+/- 0.16 mm (3σ)**	**88%**
Lateral Translations ***(Margin shown without Translation Platforms. Actually, Translation Platforms are used)***	▪ **+/- 1.6 mm** ***(16 arcmin)*** **(3σ)**	▪ **+/- 1.2 mm** ***(12 arcmin)*** **(3σ)**	**33%** ***(Note: the use of Translation Platforms obviates this margin)***
Jitter (excluded from the Image Position Knowledge requirements)	▪ **200 milliarcsec (3σ)** **over 200 msec**	▪ **20 milliarcsec (3σ)** **abs. worst case over any period msec** By Reaction Wheel momentum management in a 5 RW configuration, a steady state jitter of .2 milliarcsec is achievable	**>900%**

▪ ***Note: one mm corresponds to ~10" at 20m***

Slew Margin

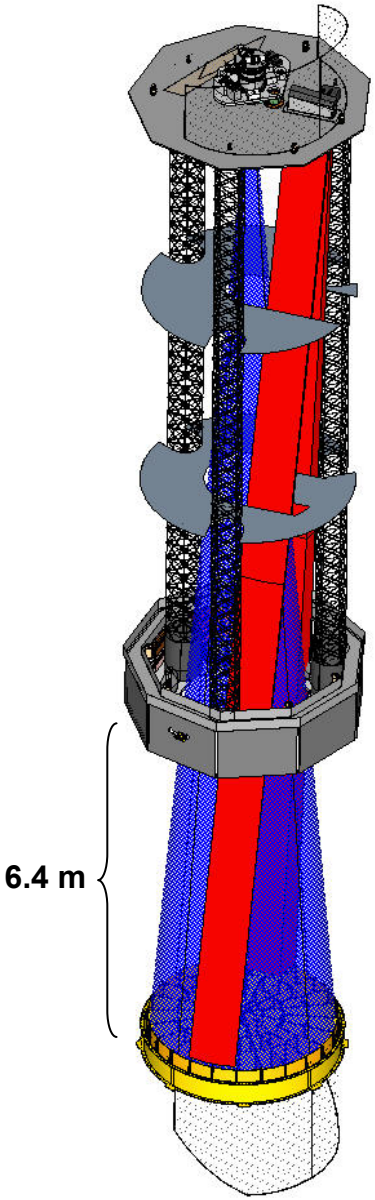
- Requirement
  - Complete a 60 degree (yaw) slew in 60 minutes (stop of Observation - to - start of next Observation)
- Slew Performance
  - 60 deg yaw completed in 0.52 hrs (92% margin)
  - 20 deg pitch completed in 0.41 hrs (144% margin)

Interesting Aspects of Observatory Configuration

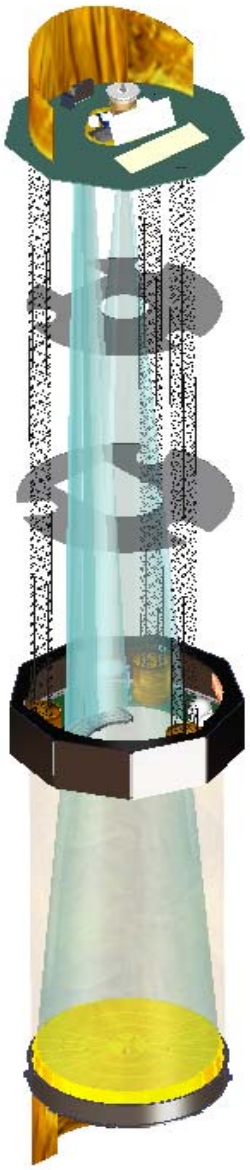
Beams thru Observatory Core

X-ray Traces

- The X-ray traces of the FMA and XGS traverse nearly the entire length of the observatory
- Either Critical Angle Transmission Grating (CATG) or Off-Plane Grating (OPG) XGS can be accommodated
- The x-ray beams drive the size, shape and placement of the spacecraft bus "ring"
  - Needs to be forward of the FMA for sufficient volume for bus components
  - Distance between the bus and the FMA limited to fit in the Atlas V 5 medium fairing
  - (CG, mass propellant lines are additional considerations)



CATG XGS

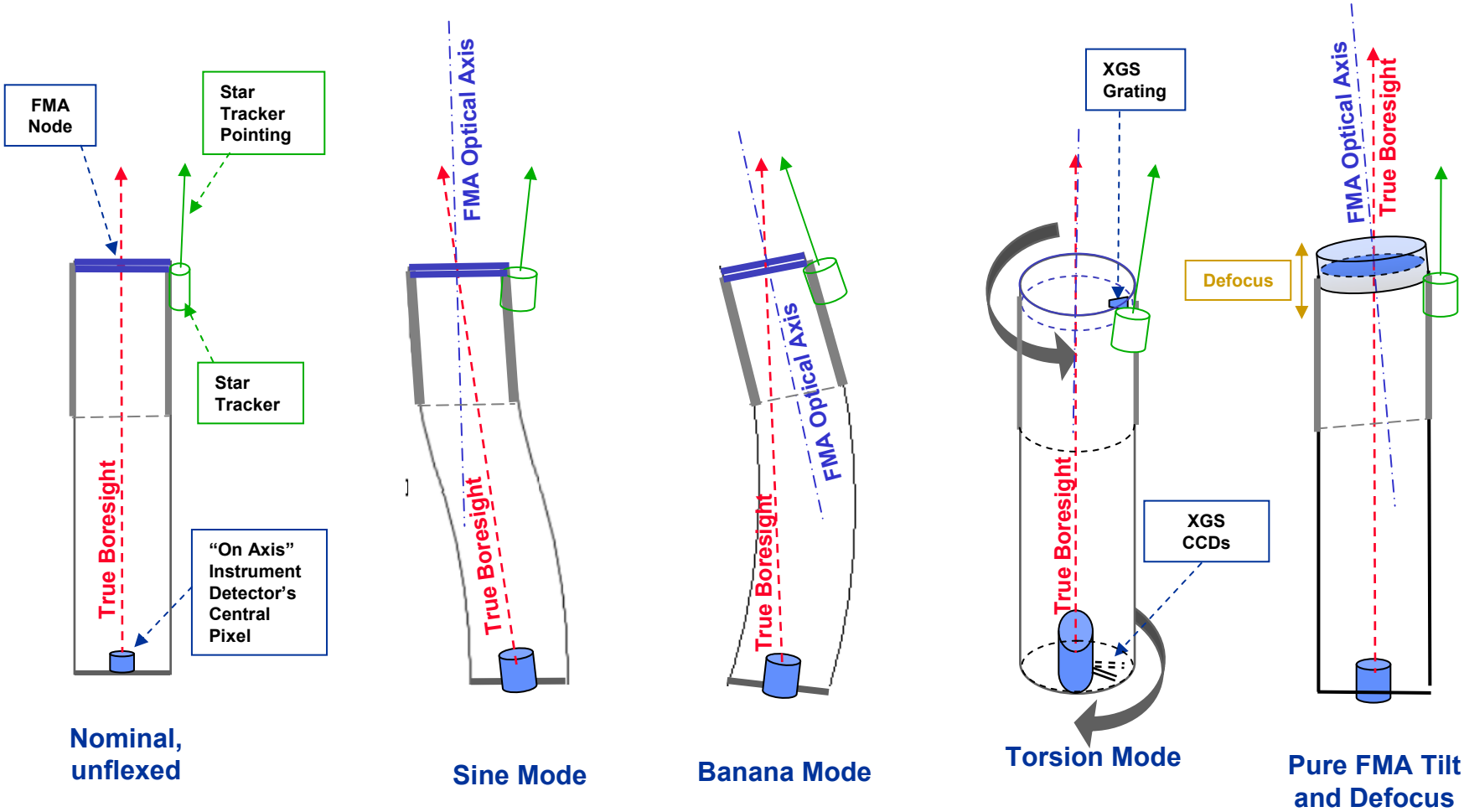


OPG XGS

Interesting Pointing Issues

Flex Body Effects and Structural Misalignments

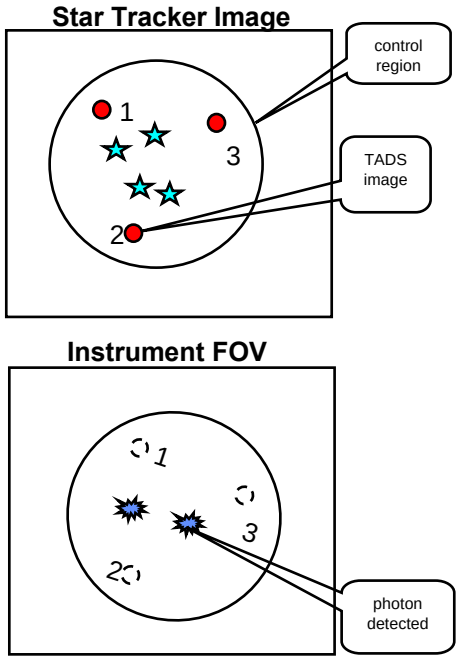
Boresight to Star Tracker and Boresight to FMA Optical Axis Misalignments

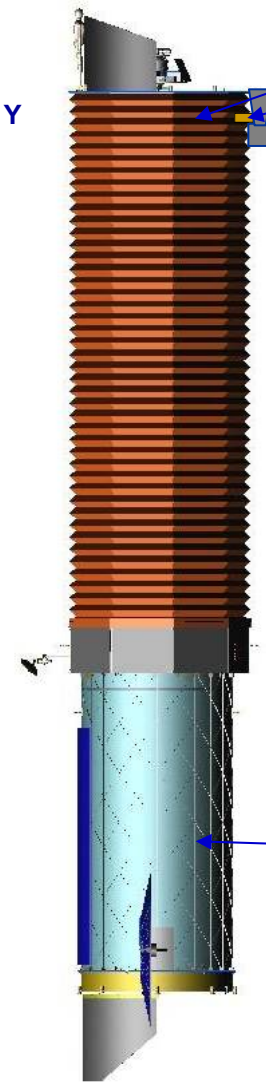


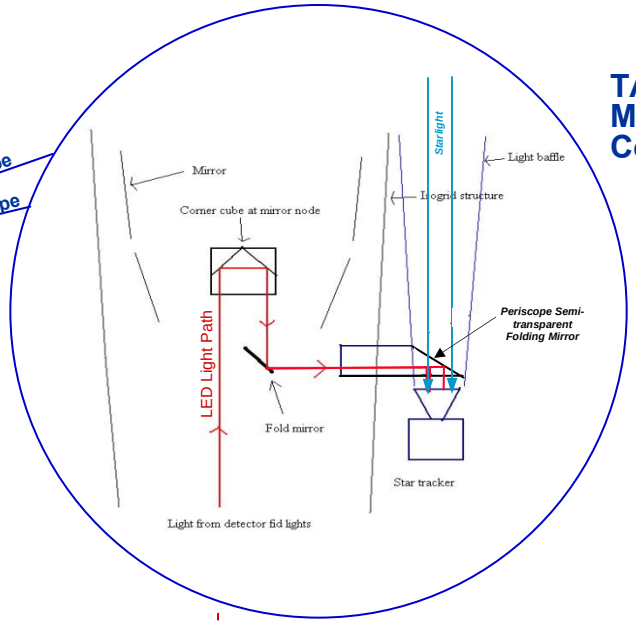
Telescope Aspect Determination System (TADS)

TADS Requirements

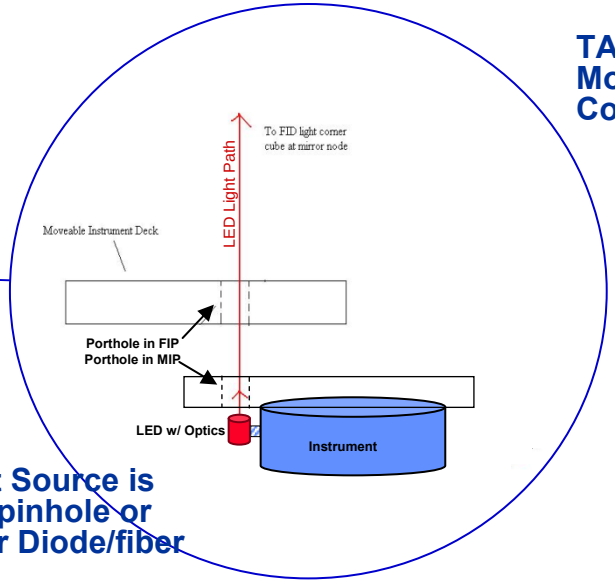
- **Accuracy:**
  - 0.8 arcsec (HPD) (.08 mm) in X and Y
  - 10 arcsec (HPD) (.08 mm) in in Torsion
- **Dynamic Range:**
  - +/- 100 arcsec (10 mm) in X and Y
  - +/- 20 arcmin (~10 mm) in Torsion







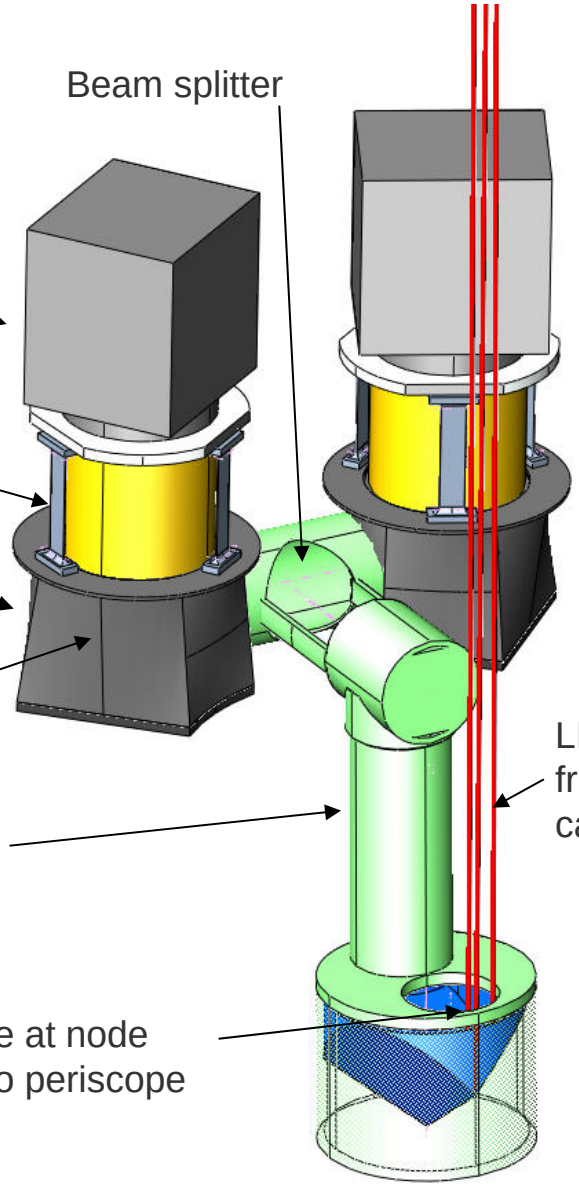
TADS Optics Module Components

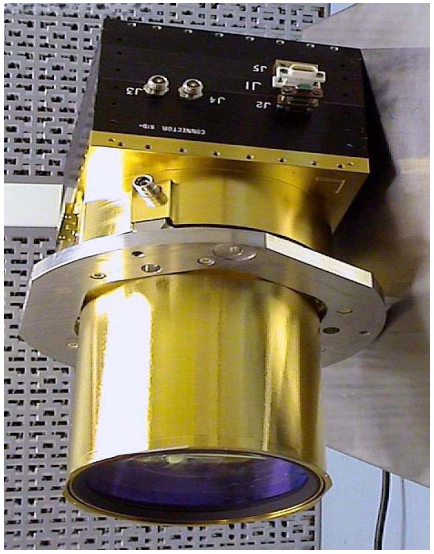


TADS Instrument Module Components

Light Source is LED/pinhole or Laser Diode/fiber

TADS Components



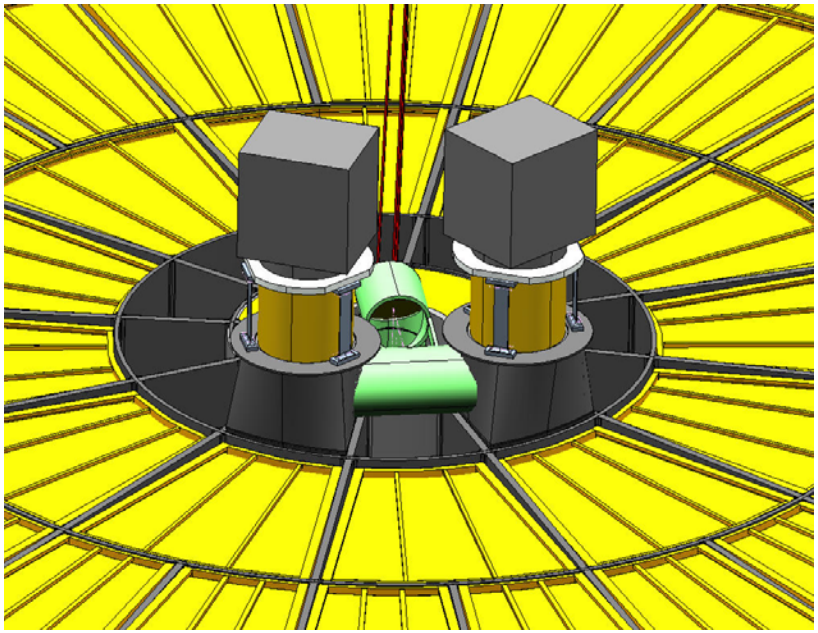


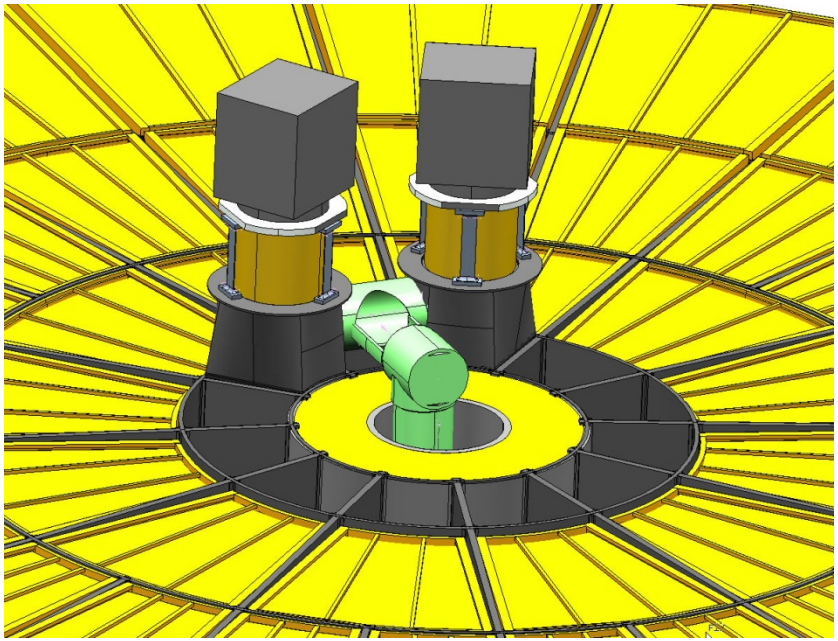
AST-301 Tracker

FID Light (LED light) assembly, 45mm long

TADS

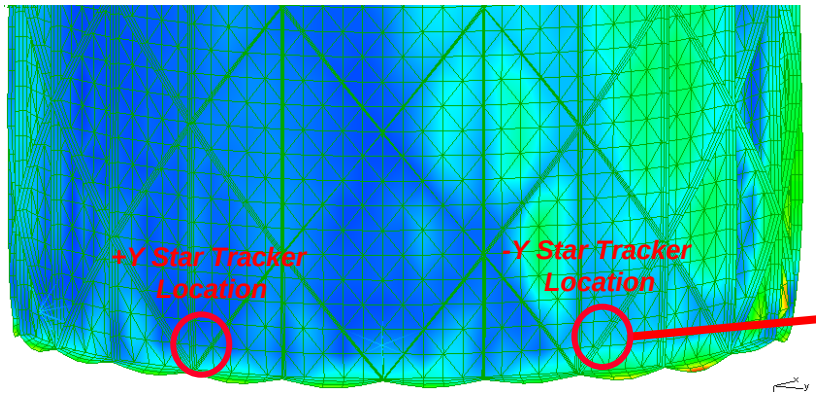
- A lightweight stand elevates the tracker lens assembly about 12 cm above the FMA.
- The periscope tube enters the stand where a fold mirror is located to turn the beam up and into the tracker FOV.
- Tracker mounts to 3 blade flexures via its Invar mounting flange.
- Flexures mount to top of the stand.





Integrated Thermal Distortion Analysis Result

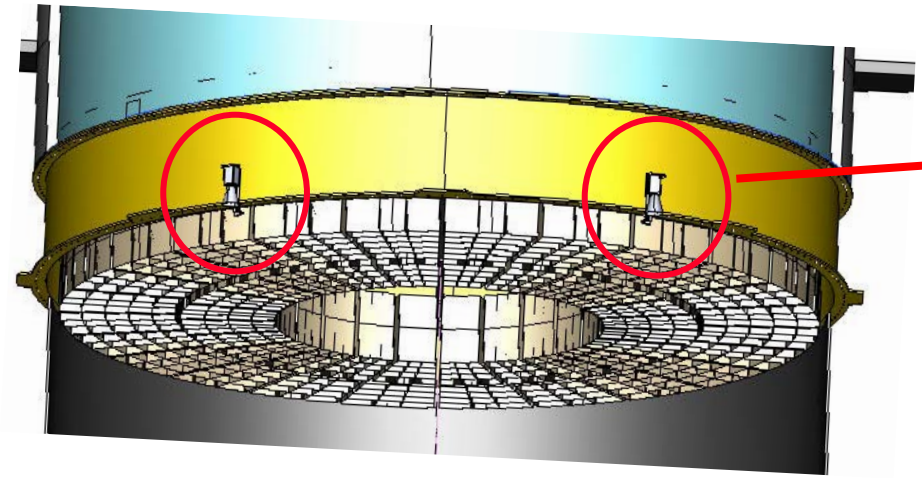
- **Prediction: Star trackers mounting surface deflections > 2 arcsec**
  - **Requirement: < 0.1 arcsec !**

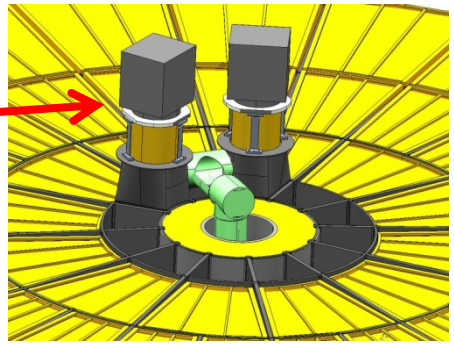


Slew From Pitch_0/Roll_0 to Pitch_20/Roll_20

	DISPLACEMENTS						
LOCATION	POINT ID.	X (mm)	Y (mm)	Z (mm)	RX (asec)	RY (asec)	RZ (asec)
FMA Avg	20096	0.0000	0.0000	0.0000	0.000	0.000	0.000
TAD Corner Cube	60857	-0.0001	-0.0002	0.0000	0.003	0.000	-0.015
+Y Star Tracker	60858	0.0036	0.0002	0.0018	1.237	2.688	-0.319
-Y Star Tracker	60864	0.0018	0.0029	0.0022	-1.738	2.312	-0.180
Image on Focal Plane		0.0052	0.0776	-0.0074	1.037	-0.079	0.199

- **Resolution: Star trackers moved from outside of PAF to center of FMA**
  - **Deflections are all within acceptable limits**



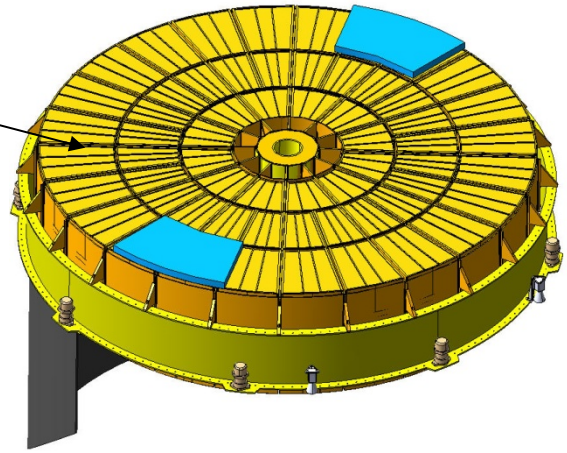


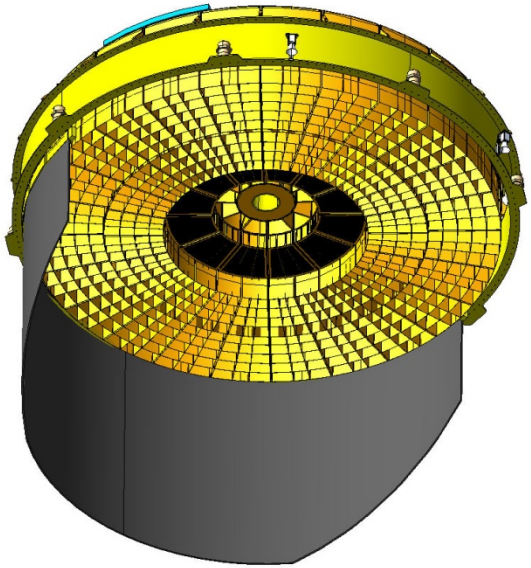
Two Gratings Approaches Complicate Matters

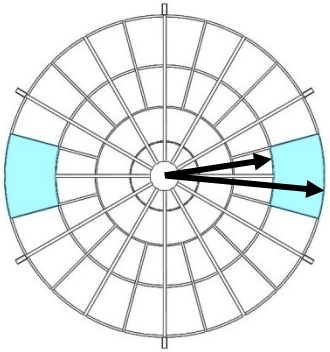
FMA w/ CAT Gratings

- Optics Module consists of the Flight Mirror Assembly (FMA), High Energy Telescope (HXT), FMA interior cover, FMA exterior cover, XGS gratings, spacecraft adapter, deployable sunshade, launch vehicle separation system, and star trackers.
- 3.24m outer diameter of FMA, 3.36m outer diameter of spacecraft adapter.
- HXT is located in the center of the FMA.

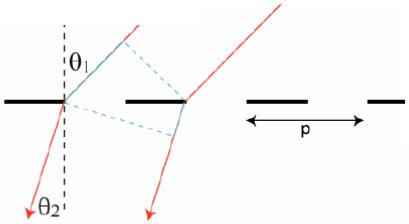
FMA Aft
(Exit) side







1125mm ID
1630mm OD
30 deg arc

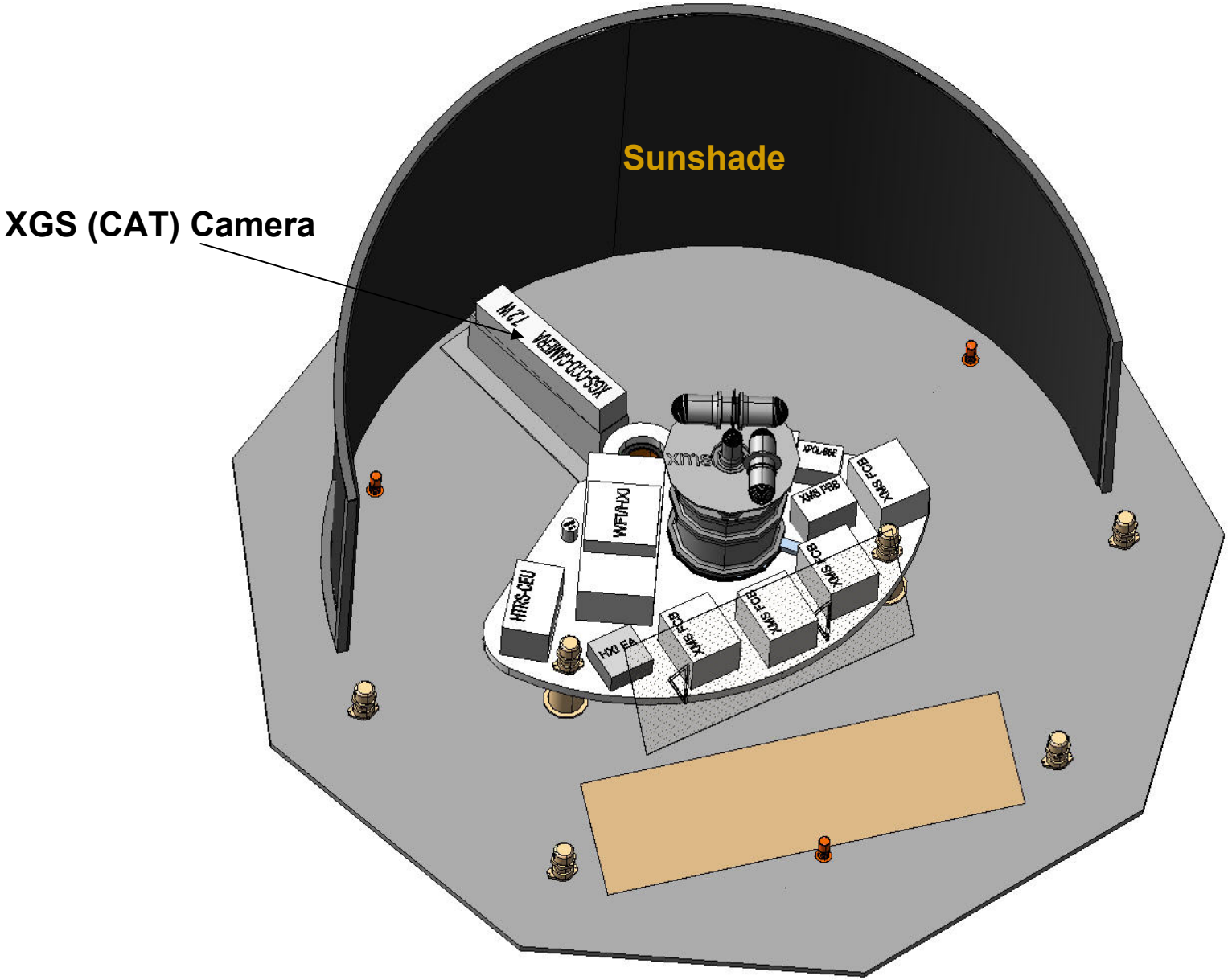


path length difference (PLD) = p (sin θ_1 - sin θ_2)
constructive interference: PLD = mλ

Grating Equation:

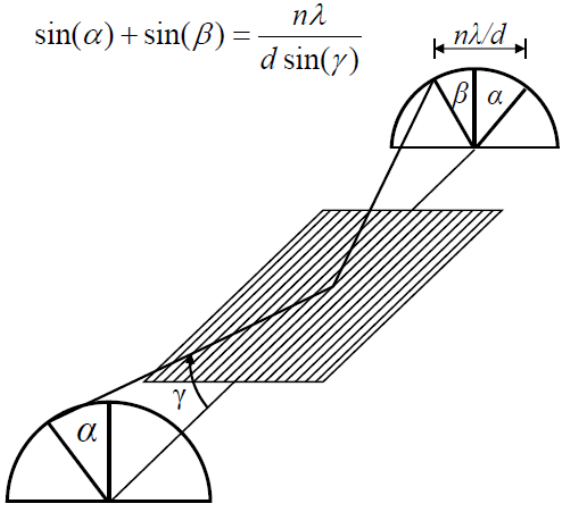
$$m\lambda = p (\sin \theta_1 - \sin \theta_2)$$

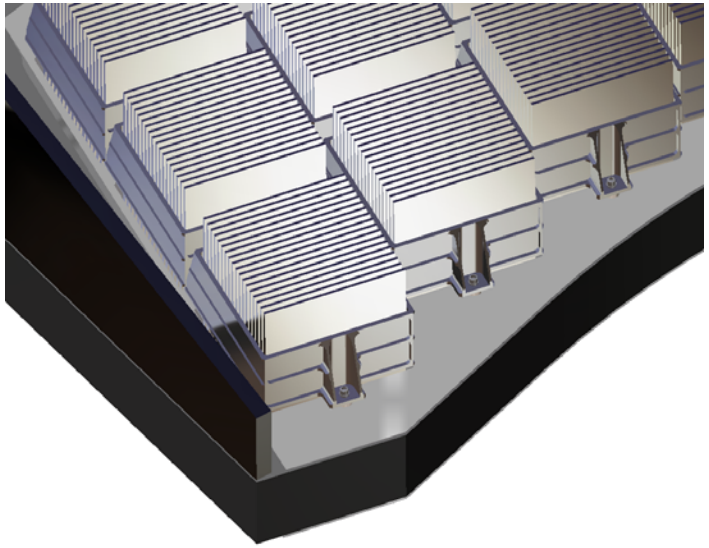
Instrument Module w/ CAT XGS CCD Camera

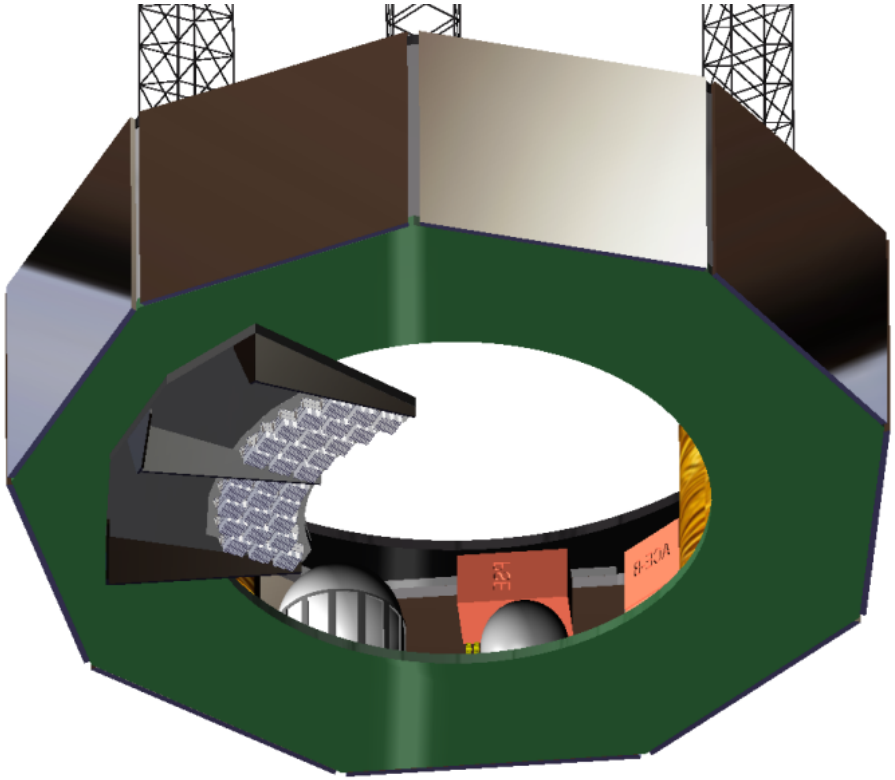


S/C Module w/ Off-Plane (OP) Grating Assy

$$\sin(\alpha) + \sin(\beta) = \frac{n\lambda}{d\sin(\gamma)}$$

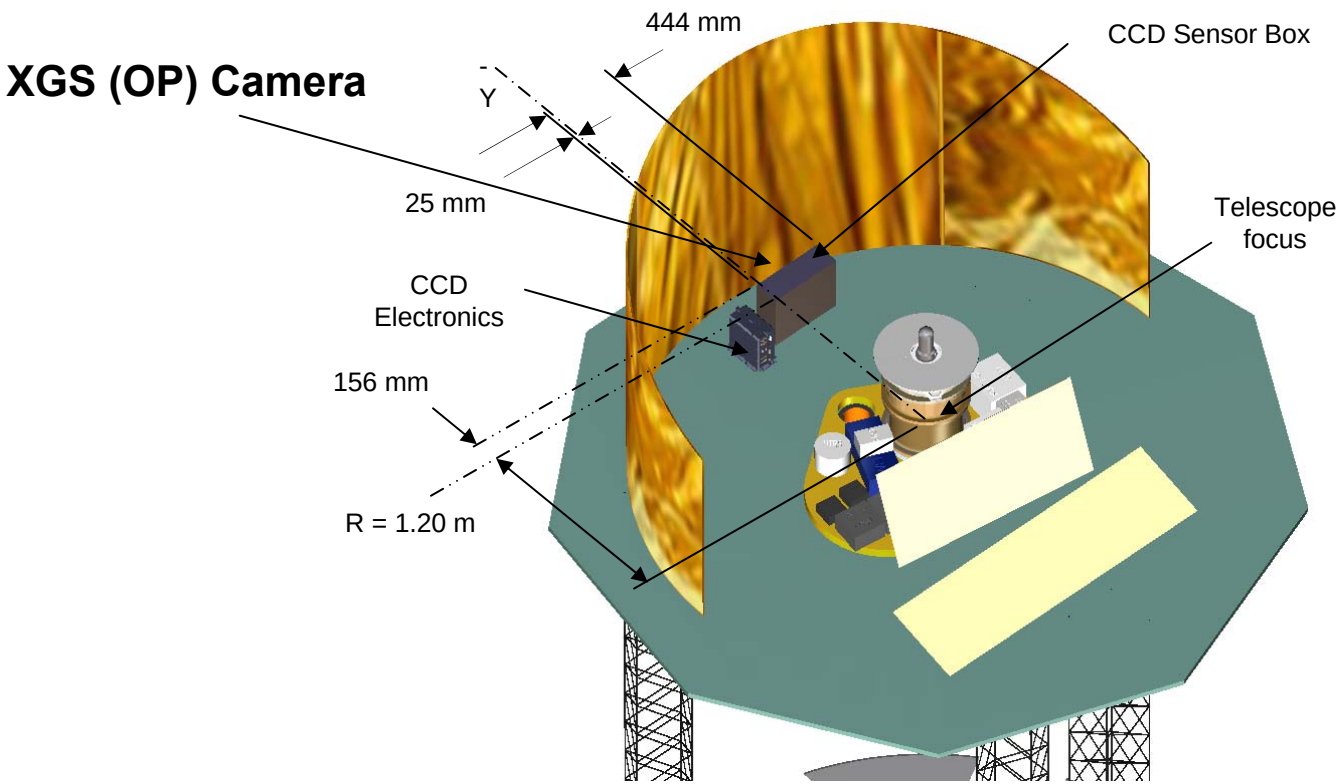


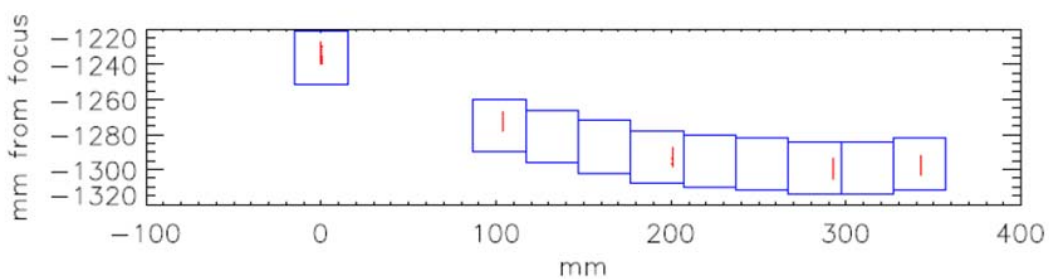




Grating Mirror Assembly Platform mounted to S/C Platform 13.5 m from telescope focus

Instrument Module w/ CAT XGS CCD Camera

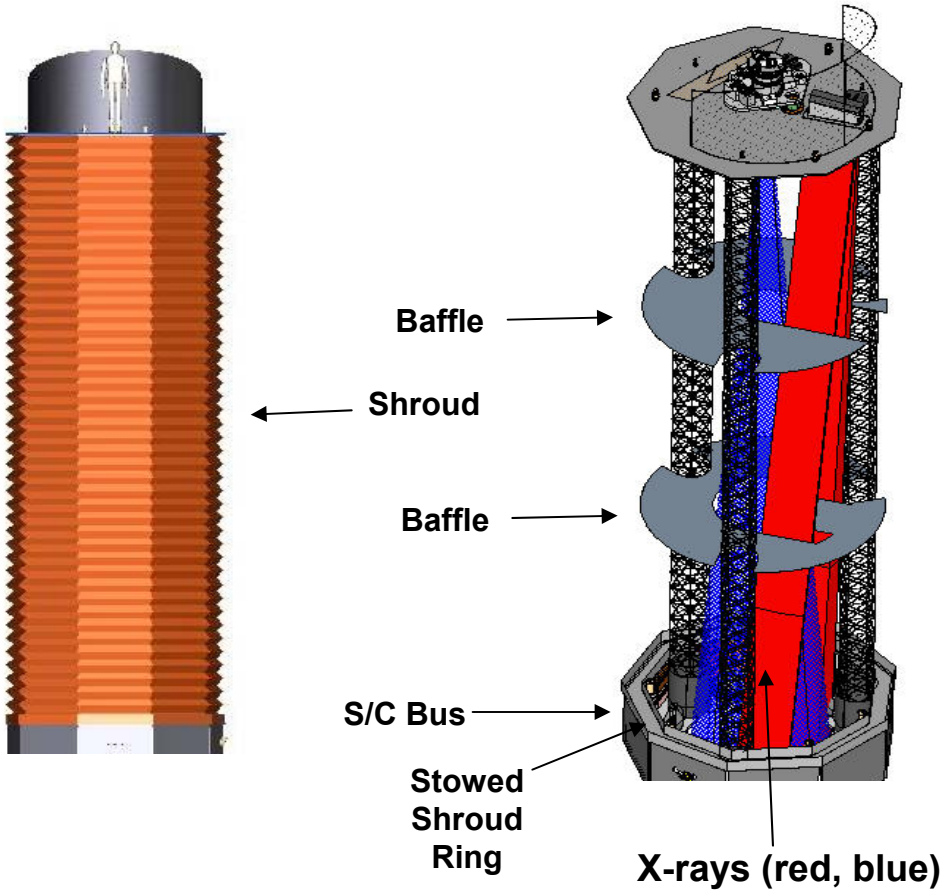




Raytrace determination of CCD position at the focal plane. Blue boxes are 30 mm x 30 mm CCDs (one for zero order camera), red lines are zero order, 12 Å, 24 Å, 36 Å, and 41 Å

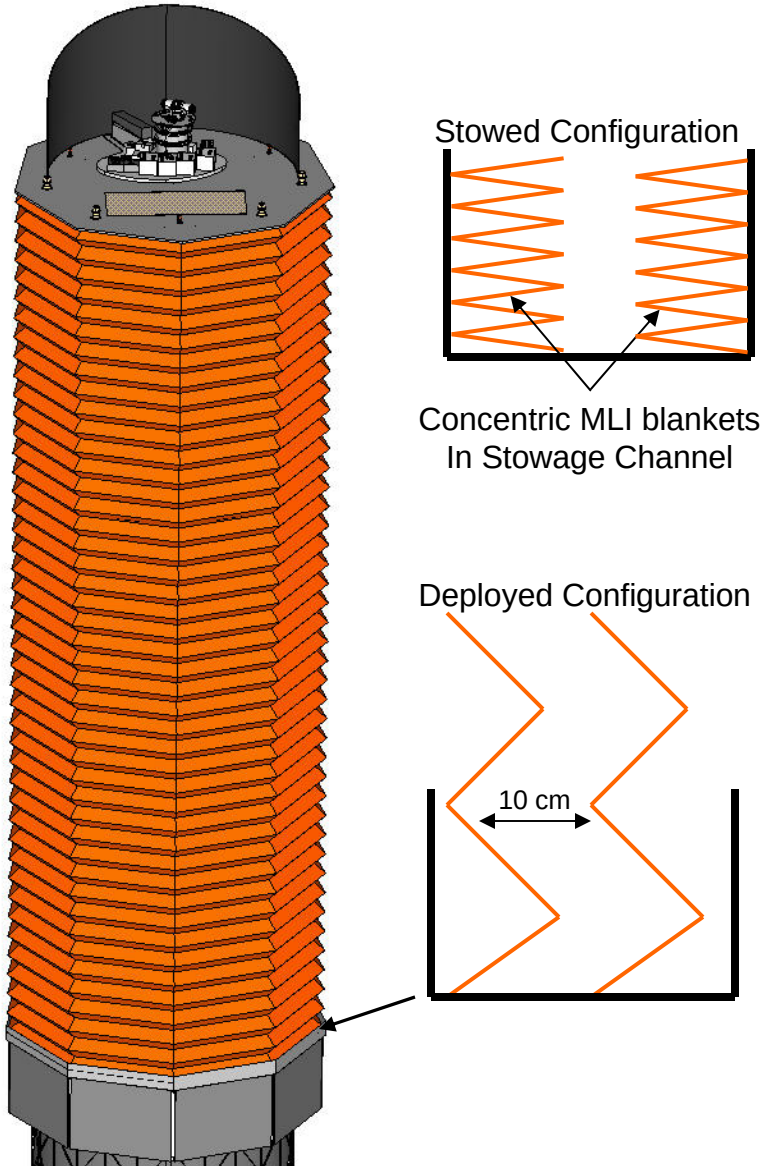
Deployment Module

- Masts deploy the IM, Shroud, Baffles, and Harness.
- Wire harness will thread through the masts for deployment similar to the SRTM and Nustar missions.
- Shroud has 2 baffles which deploy with it.
  - Baffles currently baselined as 0.1 mm thick Tantalum foil on a Kapton, Kevlar, or Mylar film.
  - Baffles have cutouts to allow x-rays to pass through, but block stray light.



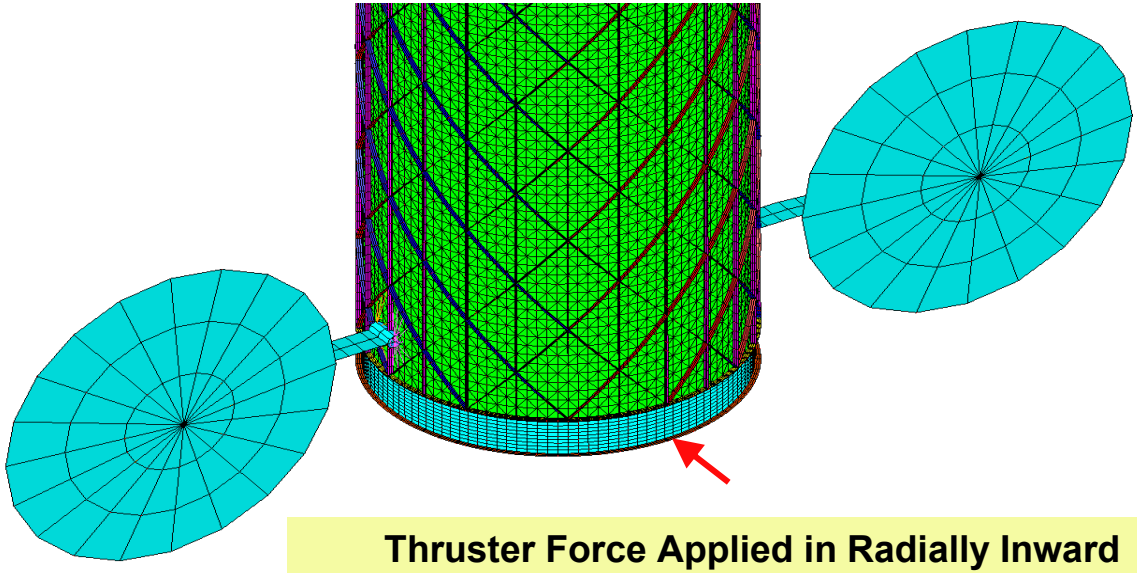
Deployable Shroud

- IXO has a deployable shroud between the IM and the Bus
  - Shroud assembly consists of 12.2m long, 3.8-3.9m diameter multi-layer insulation blankets which are pleated like an accordion or camera bellows.
  - Pleats allow the shroud to be folded up into a channel located on top of the spacecraft bus for stowage
- Blankets for a "Whipple shield" (two concentric blankets separated by 10 cm) to minimize micrometeorite punctures
  - Held apart by 2 x 18 lightly tensioned dental floss-like lanyards
  - Each blanket constructed of 5-10 layers of ¼-mil aluminized Mylar and Dacron scrim cloth with thicker inner and outer layers
  - Innermost layer black
  - Conductive external layer
  - "Whipple shield" concept lowered thru puncture predictions from thousands to 36 over 10 years
- Mass of the is 150 kg



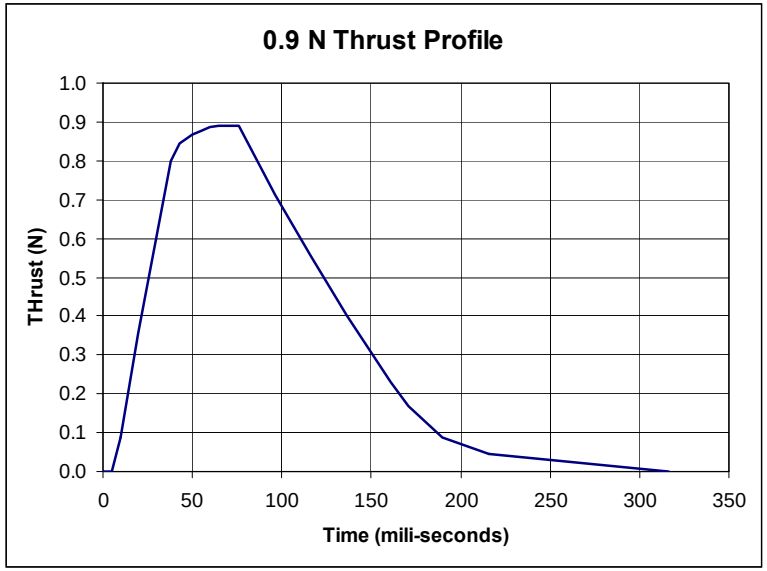
Pseudo-continuous Solar Torque Offloading

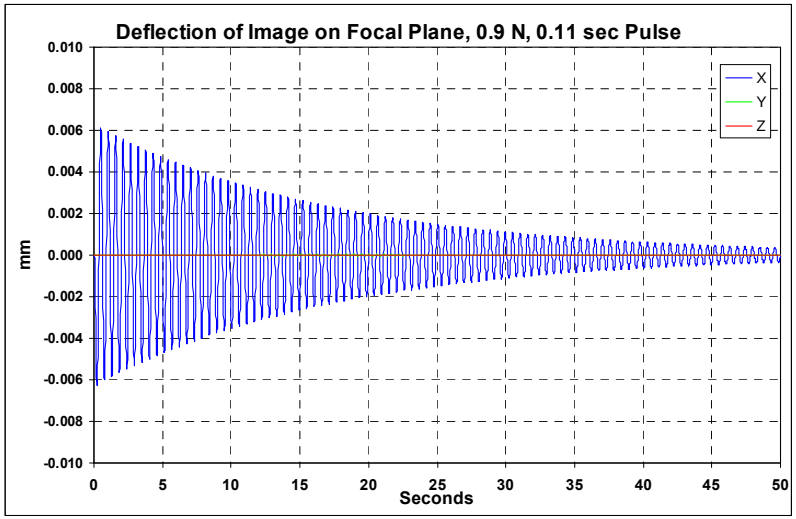
- Periodically fire 0.9 N monoprop thruster
  - 0.11 s burn every 18 minutes
- Number of 0.11 s Thruster Firings: 330,000 over 10 years
  - Voyager had over 500,000 burns from single thruster, using same thruster
- Total amount of propellant used over 10 years: 16.5 kg
  - No additional system overhead
- Orbit determination solution verified, feasible

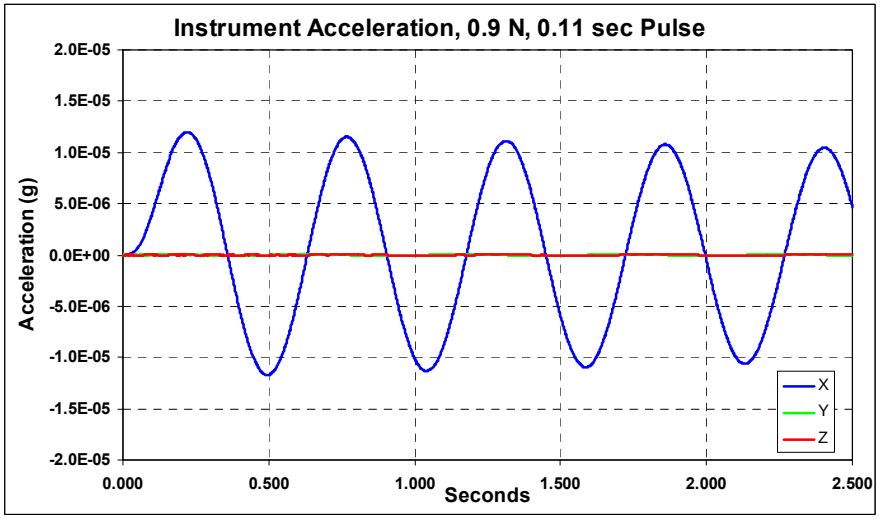


Thruster Force Applied in Radially Inward Direction to +X Side of Spacecraft Adapter Flange

Thruster Pulse and Model Parameters



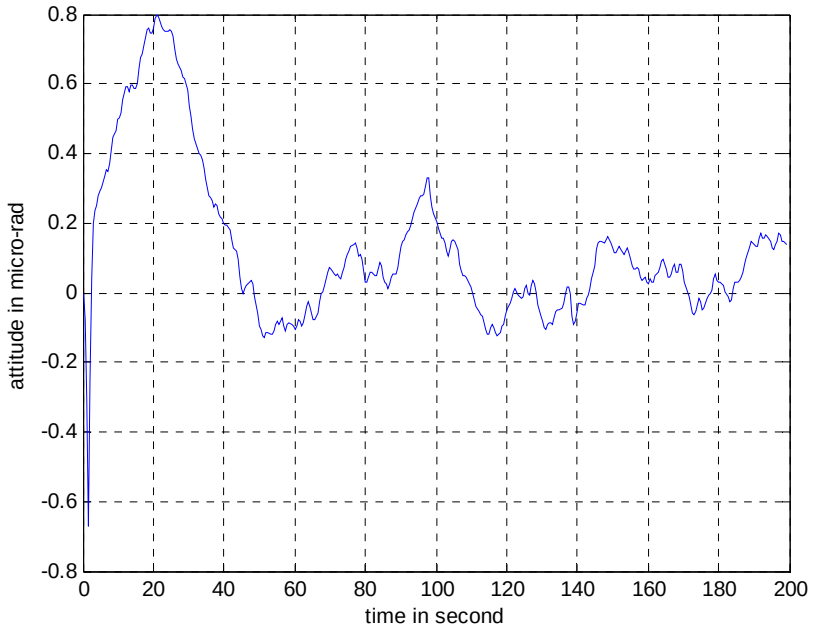




Integrated FEM + Control System Result

Temporary Attitude Deviation due to 0.9 N Thruster Firing

- 0.9 N Thruster on for 0.11 s; generates 0.1 Ns impulse and 0.62 Nms angular momentum delta
- RWL feed forward of -0.2 Nm for 3.1 seconds
- Thruster firing centered relative to 3.1 second RWL feed forward period

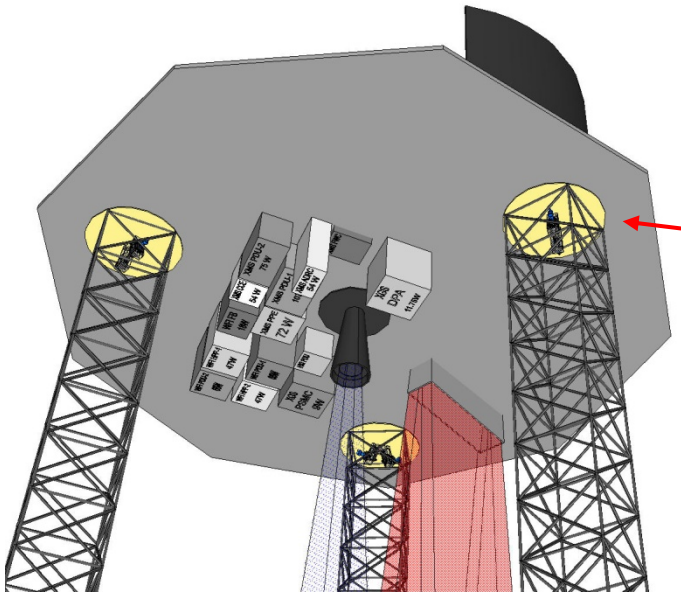


- Resulting attitude excursion about Y axis: 0.165 arcsec

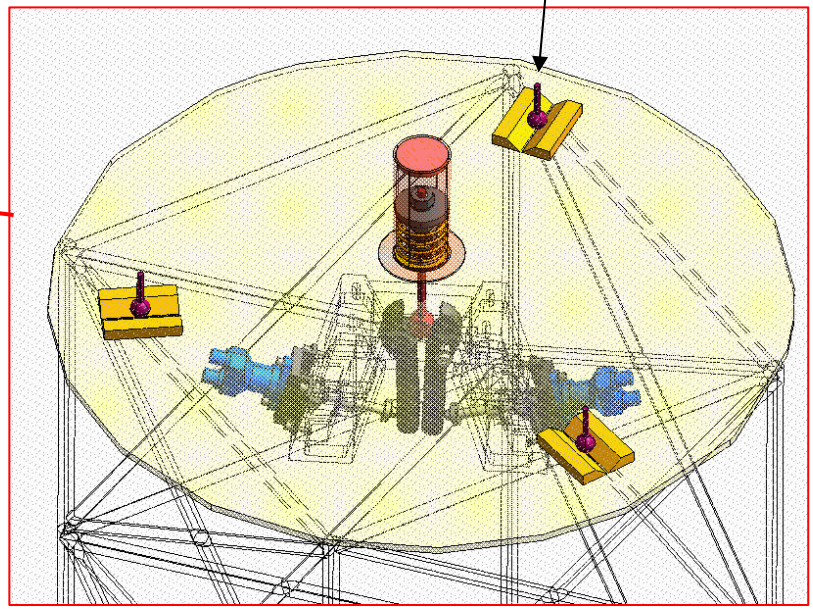
Mission Success
Contingency Measures
Risk and Reliabilities

Mast Deployment Contingency: Kinematic FIP Mounts

- Three spheres which are screwed into the FIP are compressed into V-grooves on the ADAM plate.
- This kinematic joint provides repeatable placement of the mast onto the FIP as well as providing point contact between the separating parts.
  - Point contact simplifies separation and minimizes the force required.

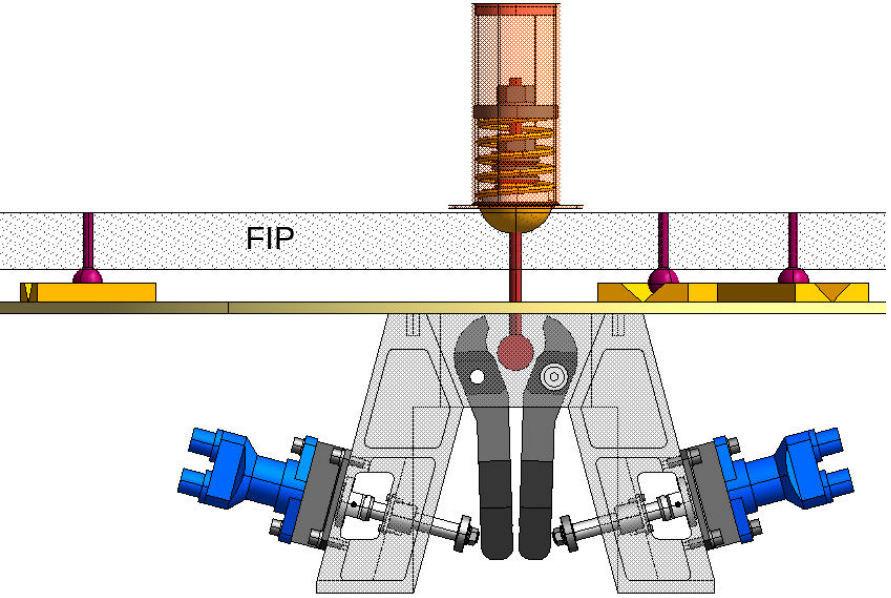


Kinematic Interface
Sphere in V-groove

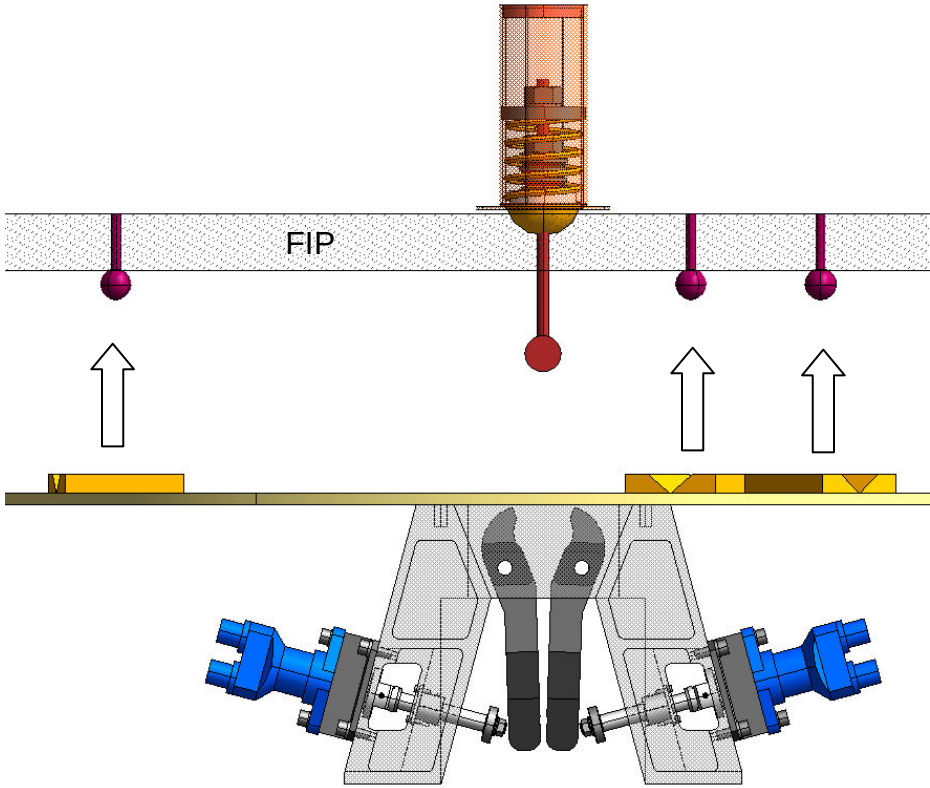


Deployment on 2 masts: Disconnecting a Failed Mast

- NSI pyros on each sep nut fire. Only one latch jaw is required to rotate to free the latch pin. After the jaws open, the FIP is disconnected from the mast and is free to move upwards as the other masts deploy.



Latch jaws open



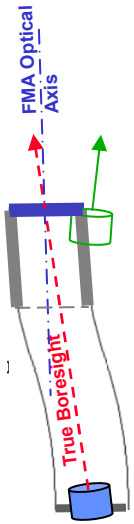
FIP is disconnected from failed ADAM mast

Focus and Translation Mechanisms

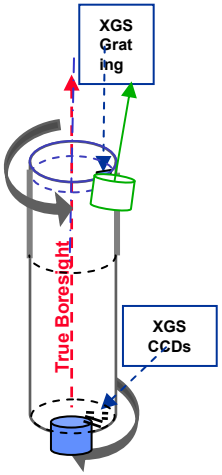
- **Focus (+/-Z) Mechanism for XMS and WFI/HXI**
  - Max. Allowed On-axis Defocus in Z: +/- .15 mm
  - Expected total Metering Structure On-axis Defocus due to all effects in Z: +/- .08 mm
  - Focus Mechanism range of motion in Z: +/- 5 mm
  - Note: On-axis Instruments don't need a Translation Mechanism, Metering Structure lateral translations induced pointing error is nulled by "Observatory Off-pointing".

- **Focus (+/-Z) Mechanism for the XGS**
  - - Max. Allowed On-axis + FIP Tilt Defocus in Z: +/- .3 mm
  - - Expected total Metering Structure On-axis + FIP Tilt Defocus due to all effects in Z: +/- .16 mm
  - - Focus Mechanism range of motion in Z: +/- 5 mm

- **Cross-dispersion direction Translation Mechanism for the XGS** (+/- Y for the CAT XGS, +/-X for the OP XGS)
  - Max. Allowed Cross-dispersion direction translation (in X for the OP) : +/- 1.6 mm
  - Expected total Metering Structure Cross-dispersion direction translation due to all effects (in X for the OP): +/- 1.2 mm
  - Translation Mechanism range of motion in Z: +/- 10 mm
  - Note: No translation mechanism is needed for the dispersion direction (+/-X for the CAT XGS, +/-Y for the OP XGS).



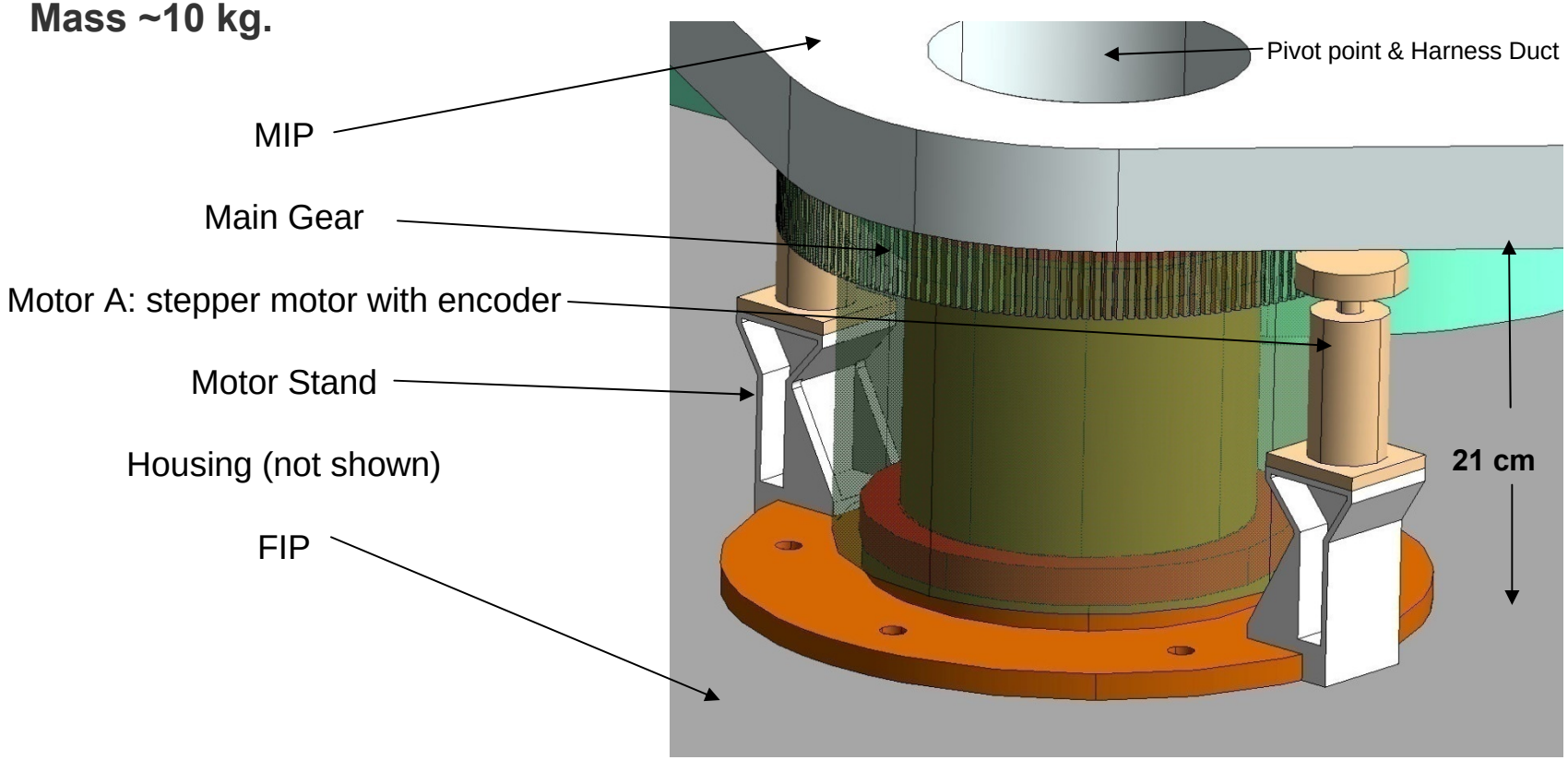
Sine Mode



Torsion Mode

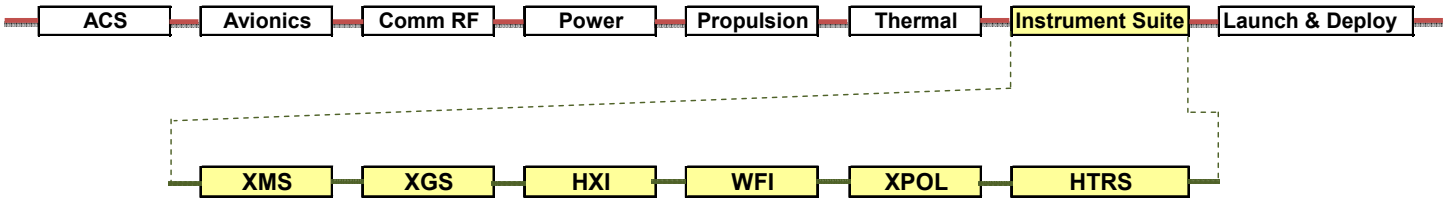
MIP Rotation Stage

- Stage consists of a large gear which is driven by two redundant electric motors.
  - Stepper motors with encoders.
  - Motors have a clutch for engagement/disengagement. Similar to cordless electric drill.
  - Motors have the usual redundant windings, and controllers, etc.
- Gear ratio, motor power, and motor size can be selected in Phase A/B when more is known about the required torque.
- Mass ~10 kg.



Reliability

- **Mission success criteria: 85%**
  - Science definition of "Mission Success" not yet clarified: assume all Instrument must work

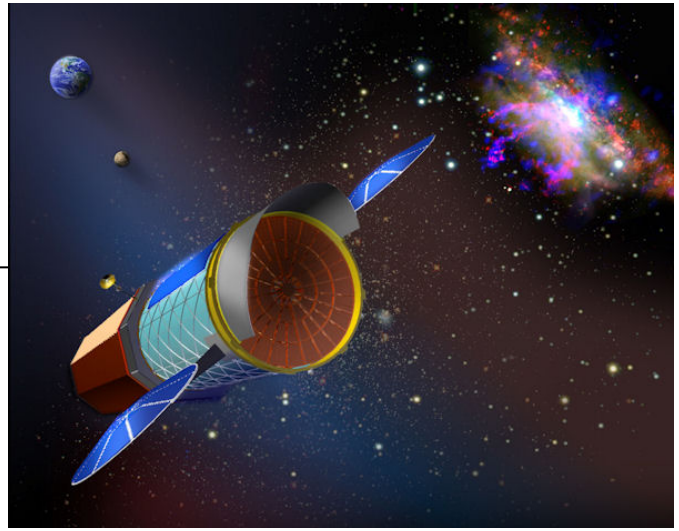


	Reliability Assessment at 5 years	Reliability Assessment at 10 years
Spacecraft Bus Sub-systems		
ACS	0.9845	0.9572
Avionics	0.9946	0.9796
Comm RF	0.9929	0.9838
Power	0.9993	0.9974
Propulsion	0.9926	0.9865
Thermal	0.9868	0.9486
SC	0.9517	0.8610
Instrument Suite		
XMS	0.9943	0.9876
XGS [requirement]	0.9788	0.9581
HXI [requirement]	0.9788	0.9581
WFI [requirement]	0.9788	0.9581
XPOL [requirement]	0.9788	0.9581
HTRS [requirement]	0.9788	0.9581
IS	0.8935	0.7975
Solar Array Deployment	0.9996	0.9996
Overall Reliability [SC, IS, L&D]	0.85	0.69

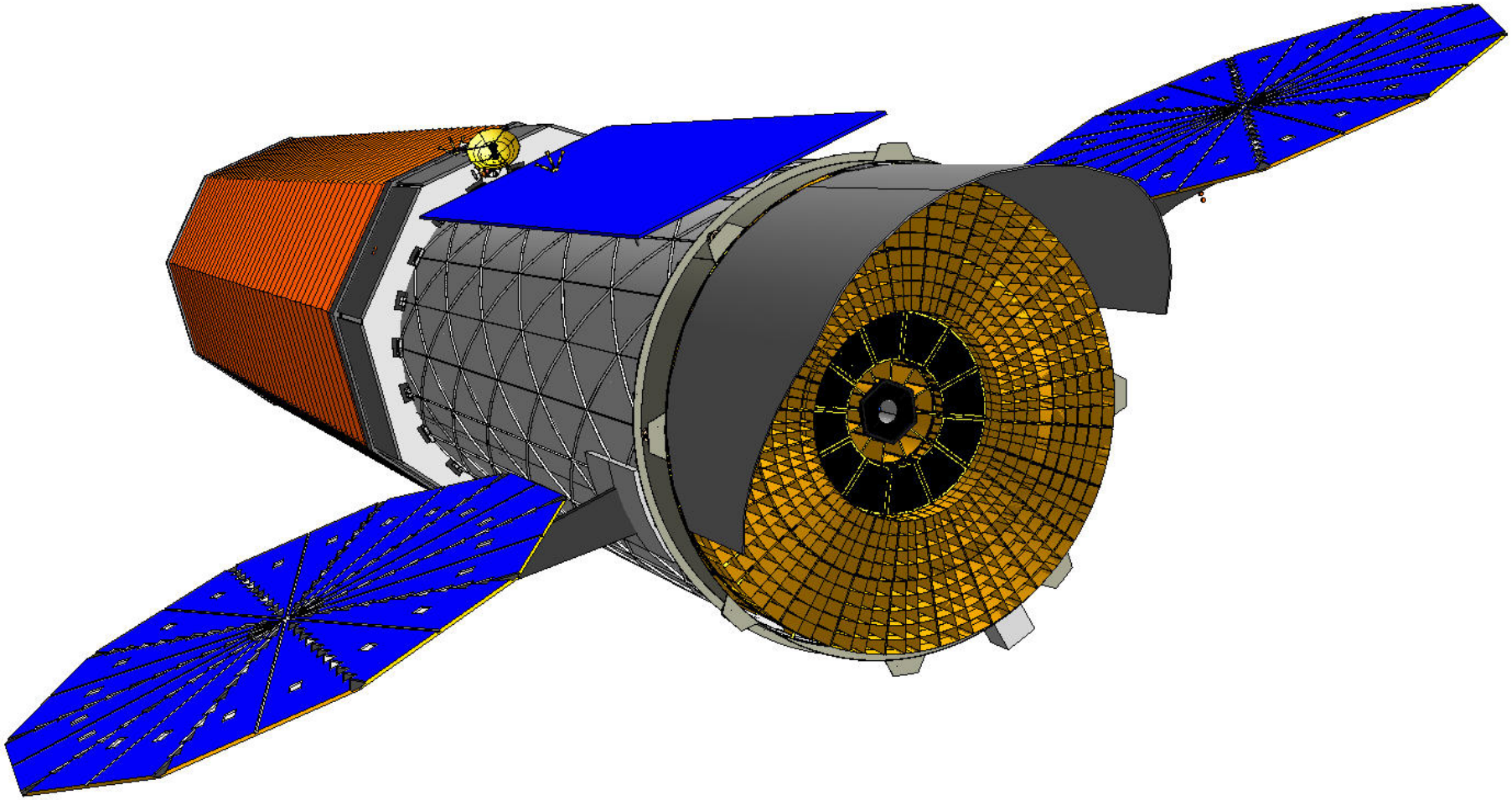
Mechanical Systems Overview

March 12, 2009

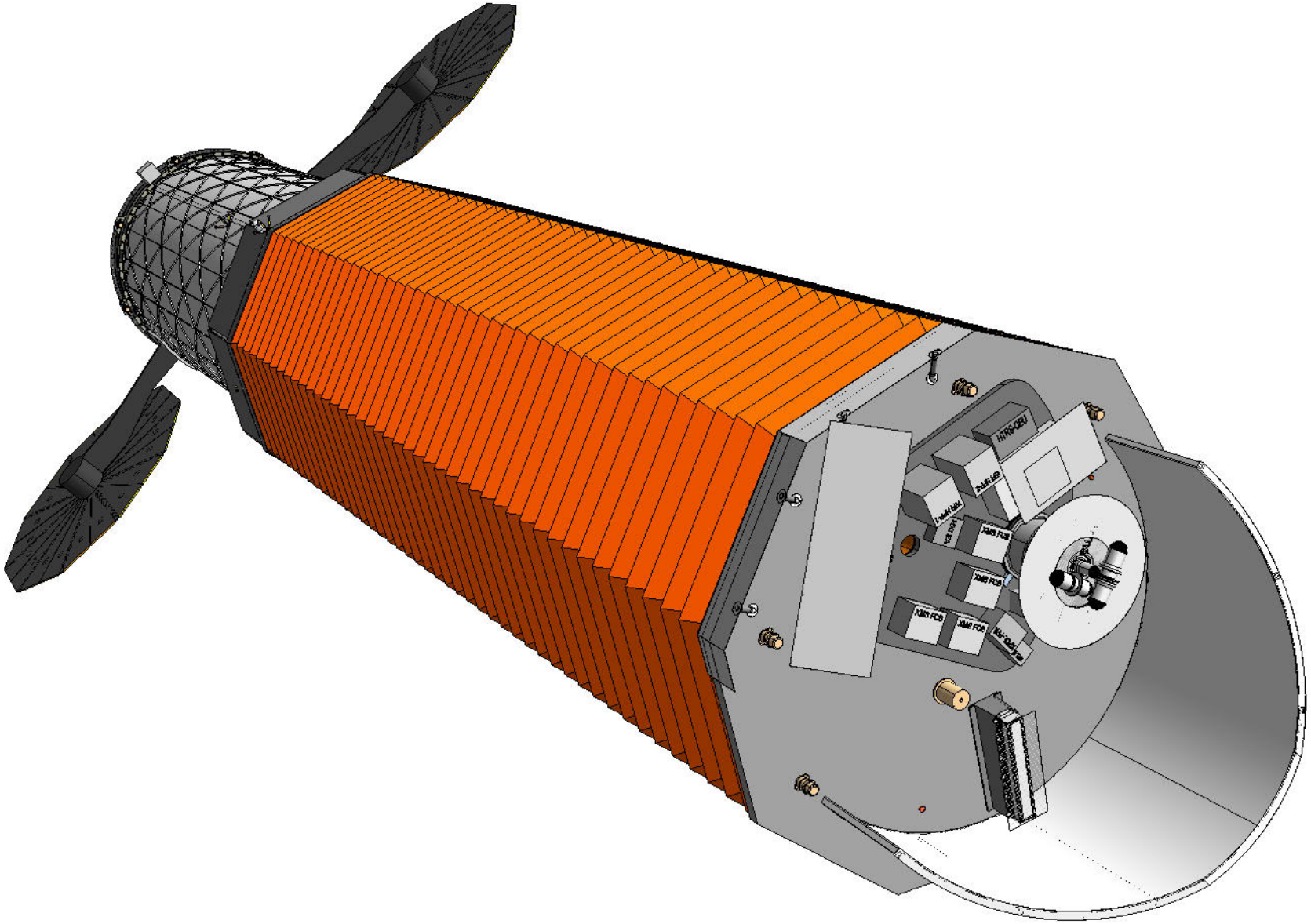
David Robinson/543



FMA View



Instrument Module View



Mechanical System Introduction

- At this stage of the project, the most important task is to understand and develop the mechanical systems level requirements (level 1 and 2)
- The primary utility for a mechanical design and configuration at this stage is to demonstrate instrument accommodation and to help develop the cost and schedule by showing that all systems and subsystems have been considered.
  - We will show that we have line items for every significant component or assembly in the systems sheets and MEL.
- The mechanical layout and configuration of IXO has evolved over several years and in many aspects has taken on a level of maturity expected for a project in Phase A.
- Being a “Facility-Class” observatory of HST & JWST size, there is far too much information to convey in this review.
  - There is a story behind every component, assembly, and system.
  - Many trades have been performed and alternatives have been explored.
- The configuration that follows meets all the mechanical requirements with a TRL >=6 and low risk.

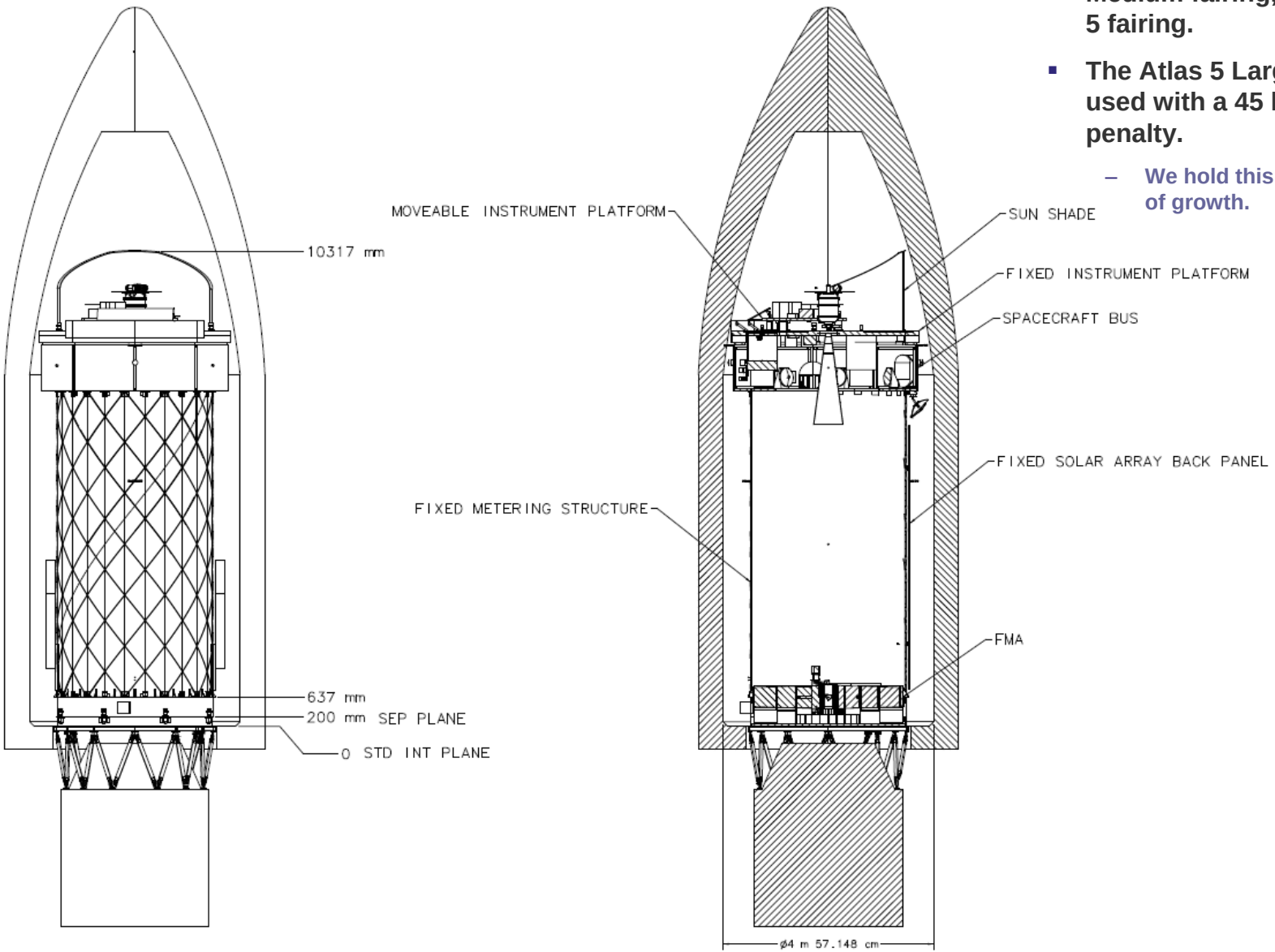
Requirements and Design Drivers

Six primary requirements drive the mechanical configuration of the observatory:

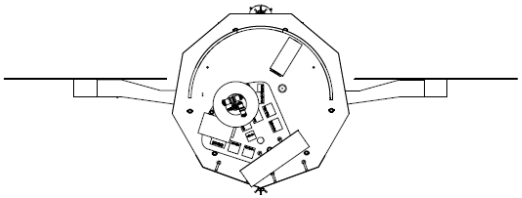
1. **IXO shall have a 20 meter focal length**
   - Drives the need for a deployable instrument module
   - X-ray beams make a very large keep out zone inside the observatory
2. **X-ray collecting effective area of the FMA shall be 3.0 m^2 at 1.25 keV, etc.**
   - Drives diameter of the FMA to 3.2m which sets the minimum base diameter of the observatory.
   - The ~2000 kg mass of the FMA favors its placement near the launch vehicle to keep the CG low.
   - 3.2m diameter FMA favors the use of a large truss adapter instead of a PAF.
3. **Instrument accommodations**
   - Drives the IM thermal design (sunshade, heat pipes, radiators)
   - Drives need for moving platform (MIP) so instruments share time at the focal plane
4. **IXO shall launch on the Atlas 5 or Ariane V launch Vehicle**
   - Envelopes the volume and mass of the observatory, sets loads & modes
5. **IXO shall have an L2 orbit**
   - Sets the throw mass of the launch vehicle
   - Sets the thermal environment (quiescent, cold)
6. **IXO shall have tight sub-arcsecond spacecraft pointing, alignment, and stability**
   - There is a budget for these items which will not be detailed here.
   - Drives use of near-zero CTE CFRP composites where possible
   - Drives the use of fine-focusing and translation stages on many instruments
   - Drives the selection of the deployment system to one that is stable, accurate, stiff.
   - Limited pitch & roll helps in the thermal area, and sets the size of the sunshades

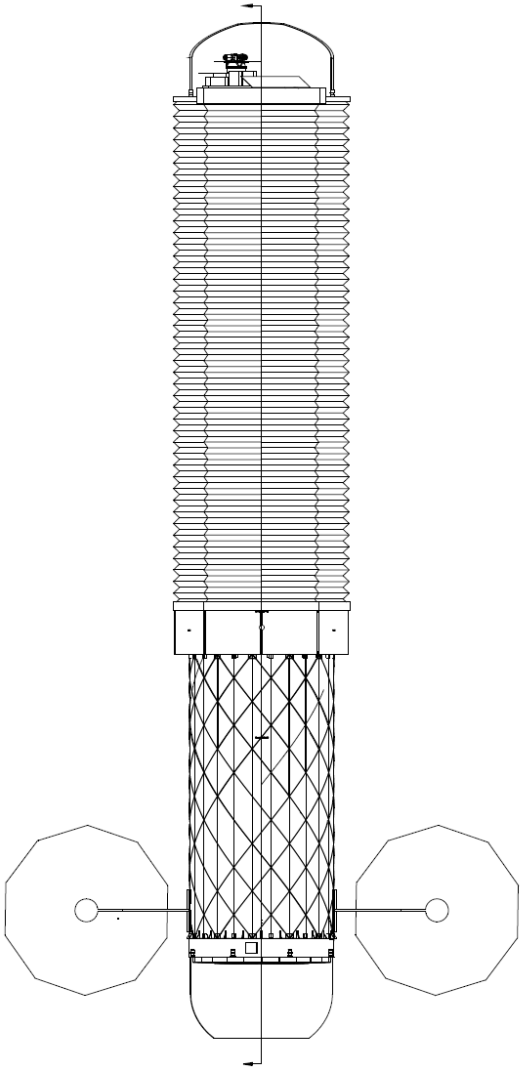
IXO In Atlas V Medium Fairing

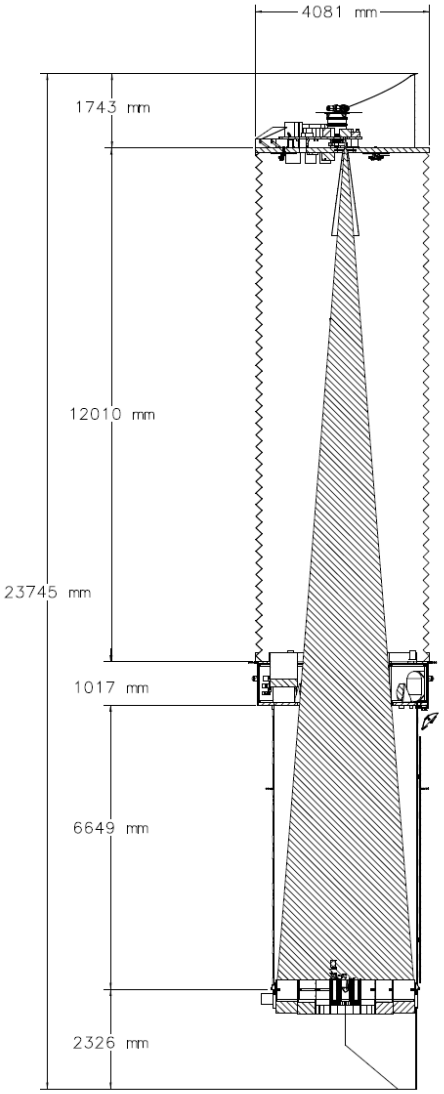
- The Observatory fits inside the static envelopes of the Atlas V Medium fairing, and the Ariane 5 fairing.
- The Atlas 5 Large fairing can be used with a 45 kg throw mass penalty.
  - We hold this in reserve in case of growth.

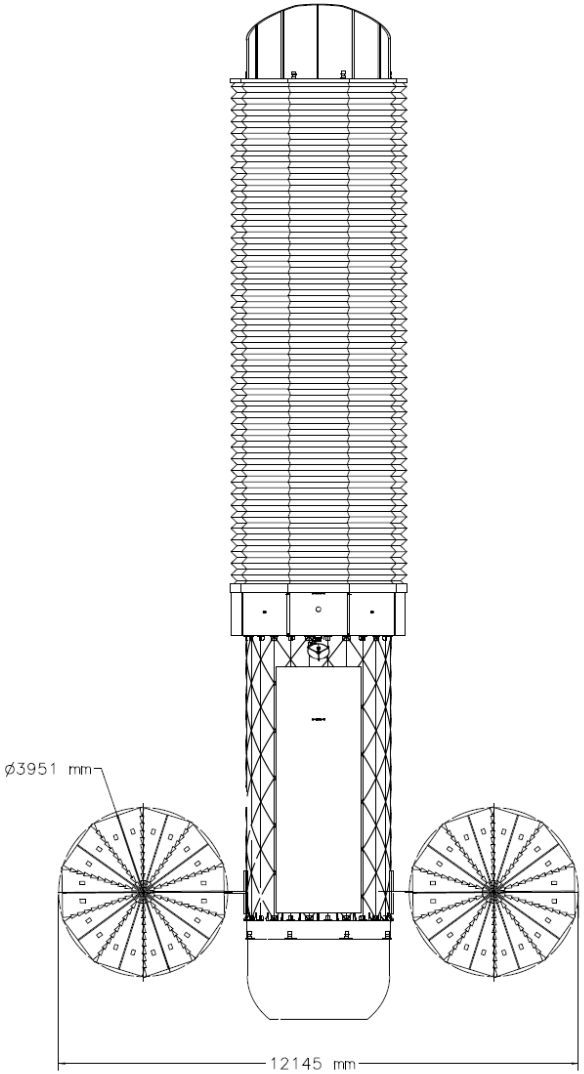


Deployed Configuration









Observatory Configuration Rationale

- **FMA was placed at the launch vehicle side of observatory**
  - Required to keep the stowed CG height limitation within allowable 5.5m above separation plane.
  - Preferred location to keep observatory 1st bending mode > 8 Hz.
  - Drives the need for a deployable FMA sunshield
- **IM placed at the opposite side of observatory from FMA**
  - Required to get the 20m focal length
- **Deployment module is needed somewhere in the middle**
- **Spacecraft Module (Bus) was the last to be placed.**
  - Couldn't put it between FMA and launch vehicle.
  - Couldn't put it "on top of" or "outside of" the FMA due to the 3.2m diameter x-ray beam which would force the Bus to exceed fairing envelope of 4.57m diameter.
  - Couldn't put it out at end of the deployed IM due to requirement to have prop thrusters bracket the deployed Center of Mass. Welded lines prevent deploying the prop system.
  - Makes the most sense to put it as far as possible from FMA on a fixed metering structure. "In the middle."
    - At 6.7m distance, the x-ray beam is only 2.3m in diameter, so the Bus diameter can be about 3.9m. Also, this is the maximum distance that the IM sunshade can fit in the fairing.

IXO On-Orbit Configuration - Four Modules

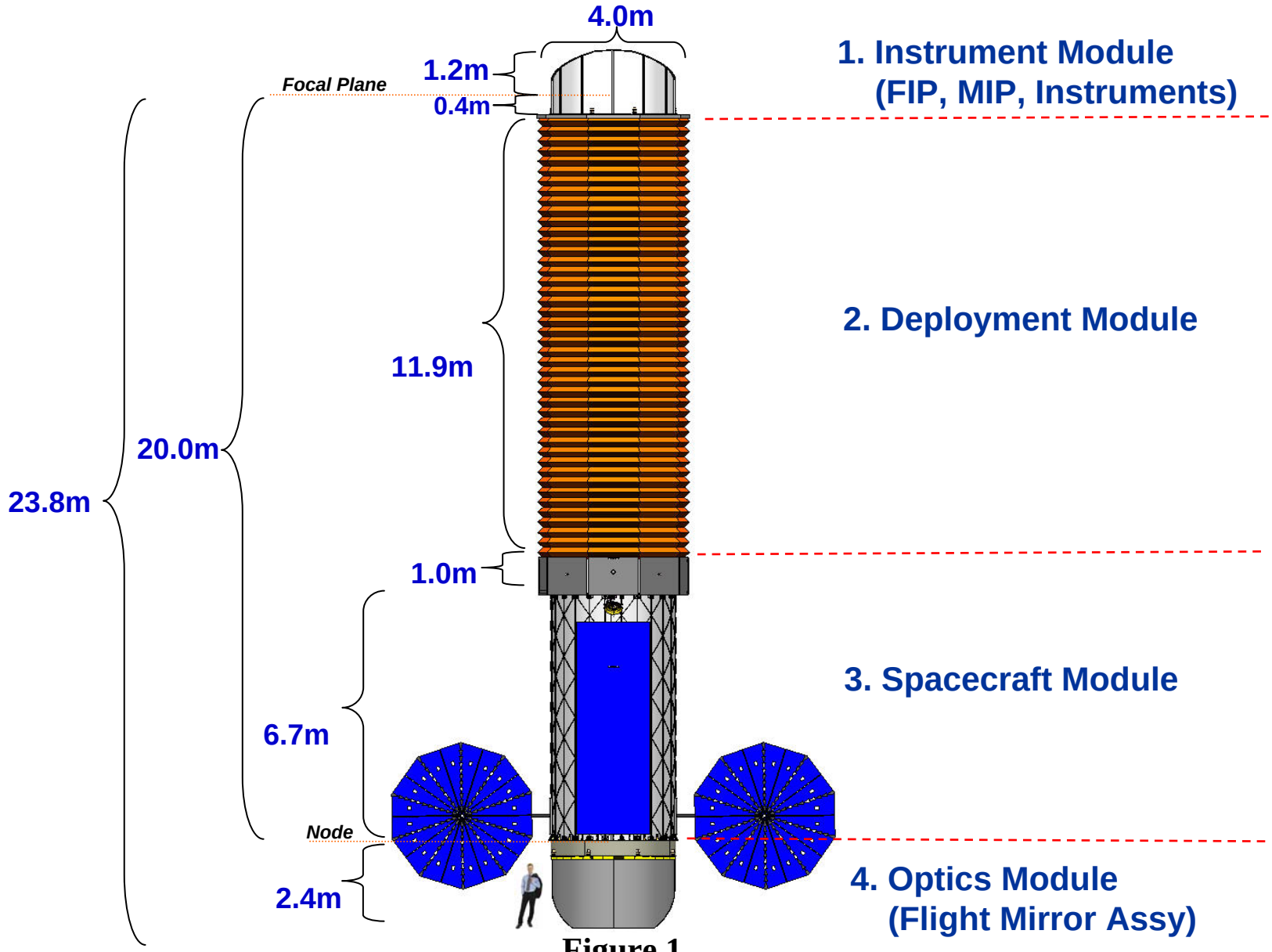
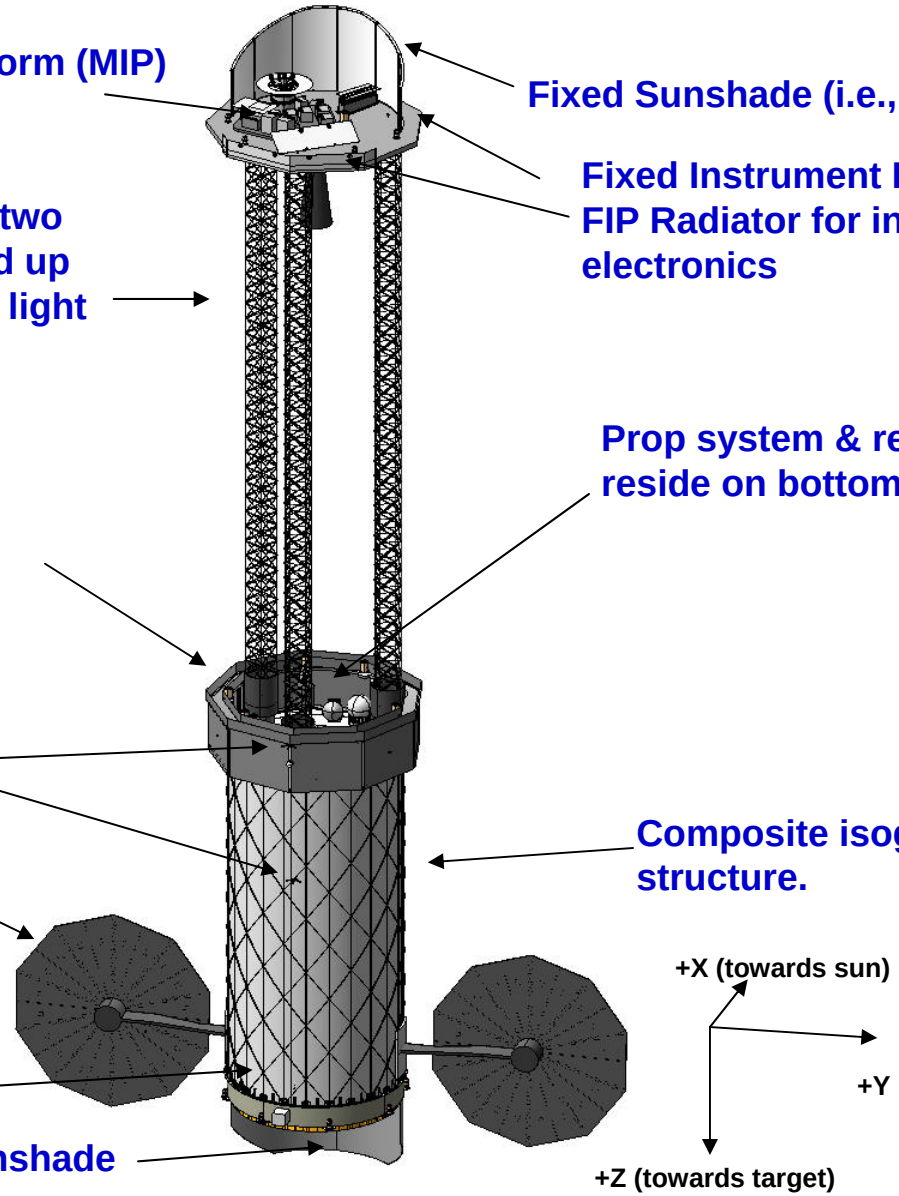


Figure 1

IXO Movie

Observatory Level Configuration Highlights



Moveable Instrument Platform (MIP) with instrument suite

Fixed Sunshade (i.e., not deployable)

Fixed Instrument Platform (FIP)
FIP Radiator for instrument electronics

A 3.9m diameter shroud and two baffles (not shown) are pulled up with the masts to block stray light

Prop system & reaction wheels (5) reside on bottom deck of bus

9-sided Bus has 4 equipment panels for the avionics: C&DH, PSE, Battery, ACS, Comm, etc.

22N Thruster Triads

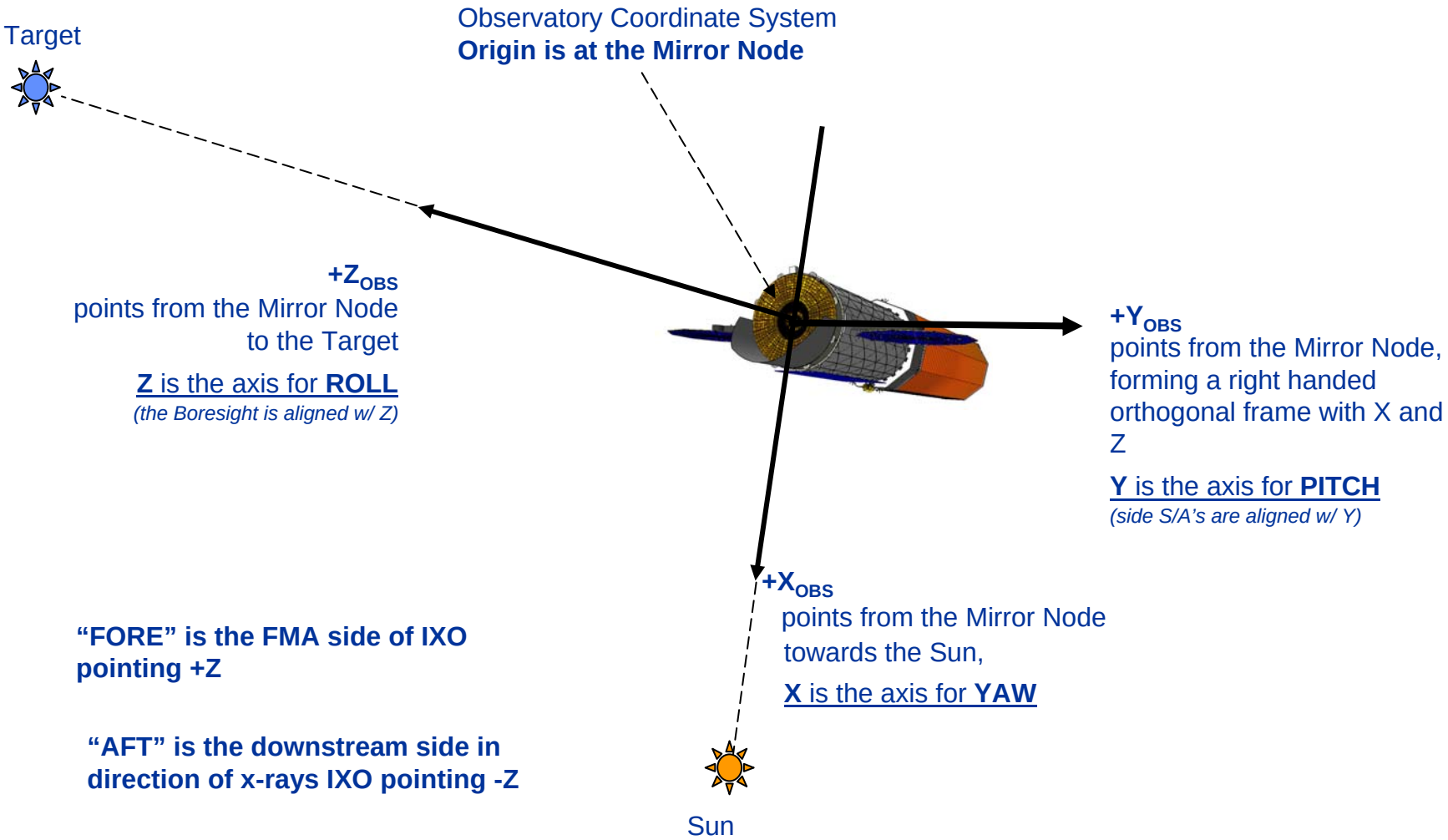
Composite isogrid metering structure.

Ultraflex solar arrays. Fixed array on +X side of metering structure

1N trim thruster

Deployable Sunshade

Observatory Coordinate System

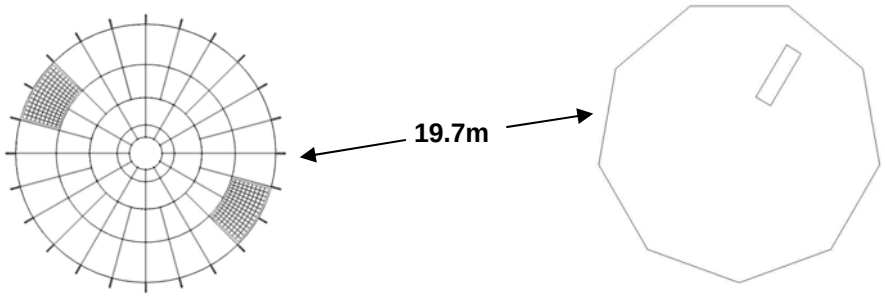


"FORE" is the FMA side of IXO pointing +Z

"AFT" is the downstream side in direction of x-rays IXO pointing -Z

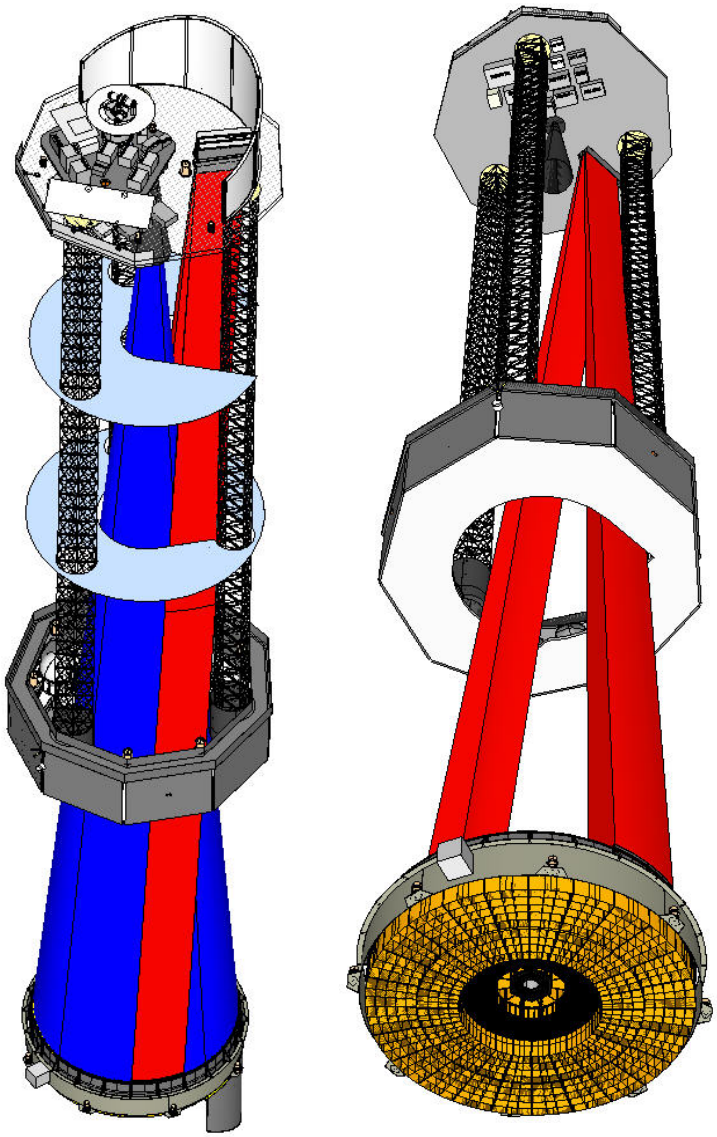
X-ray Beams Drive the Design

- The X-ray traces of the FMA and XGS traverse nearly the entire length of the observatory.
- The FMA beam is a 20m long cone with 3.2m base diameter, originating at the FMA node. It ends at the focal point.
- The XGS X-ray beams transition from a wedge shape on the aft of the FMA to a 780mm long line at their focus, with an offset of 720mm from the FMA optical axis.
- XGS x-ray beams determine the clocking of the masts, gratings, and XGS camera.



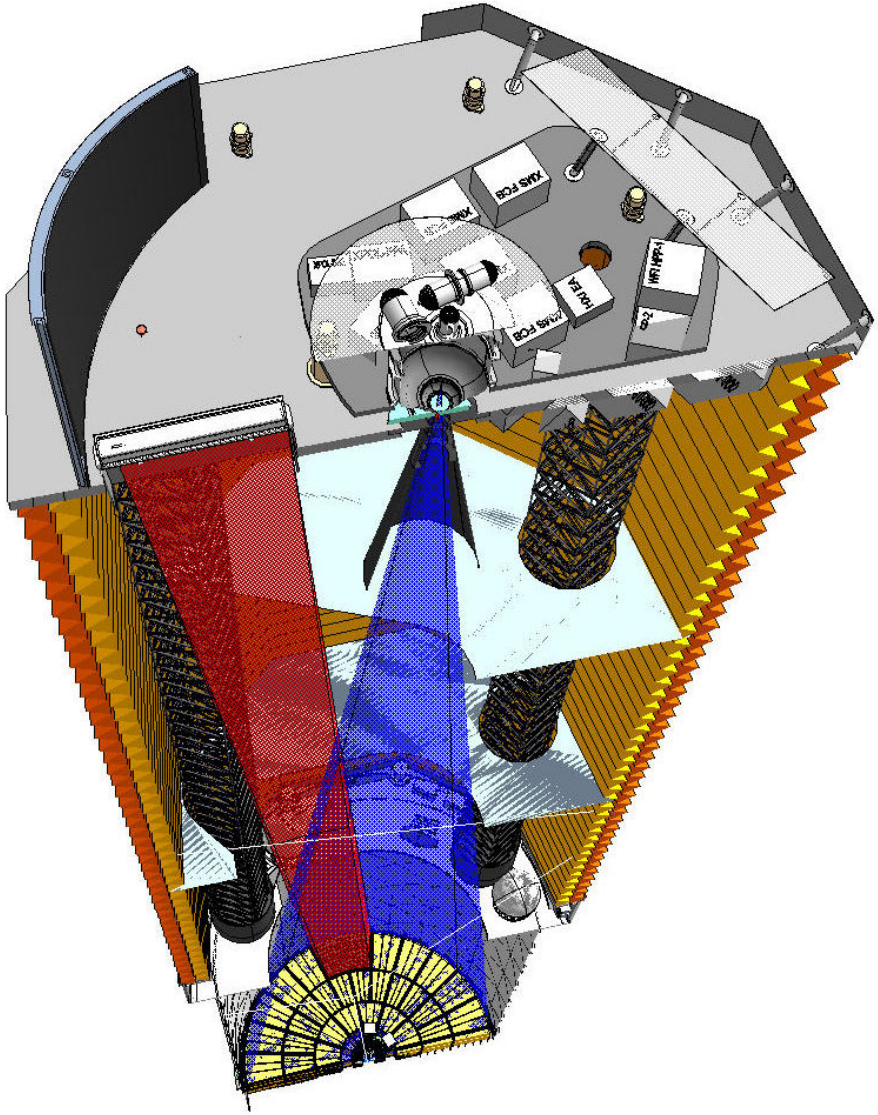
FMA with gratings

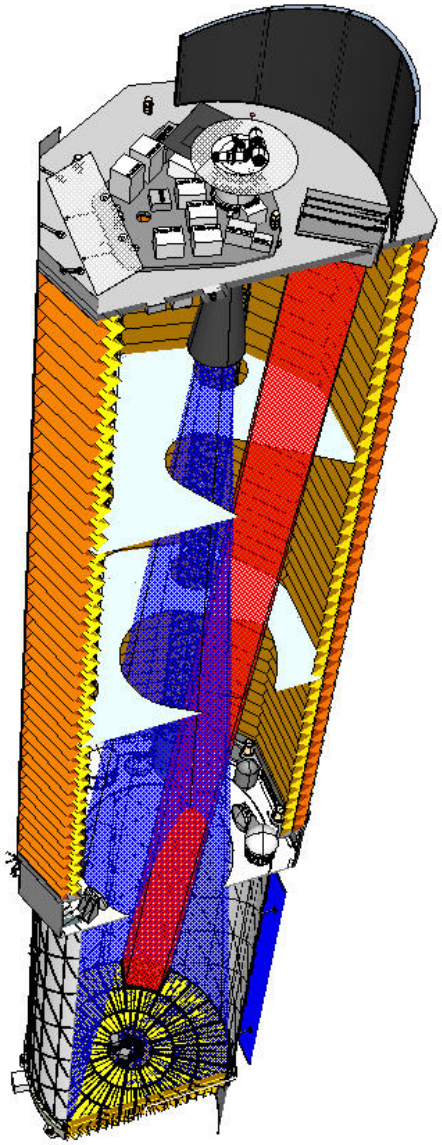
FIP with CCD camera

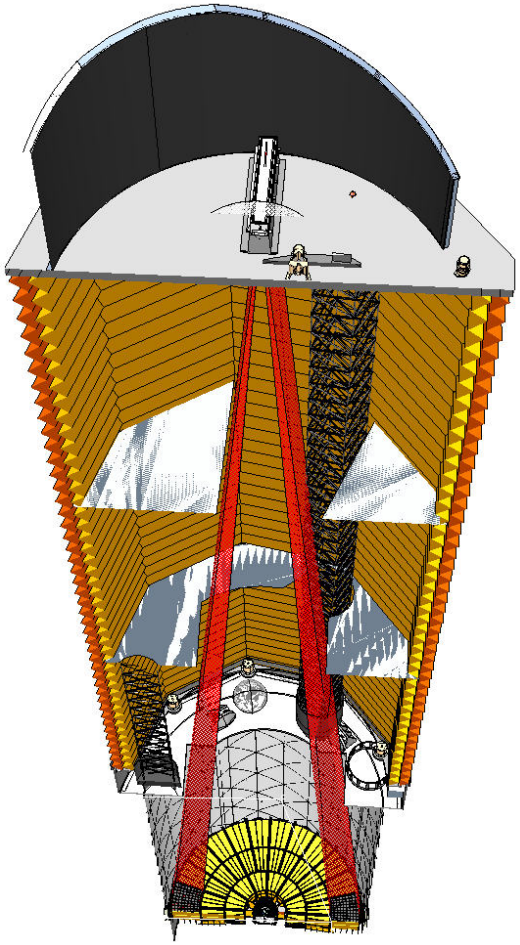


FMA X-rays (blue) & XGS X-rays (red)

Cutaway Views of X-ray Beams







Four Modules

- The observatory has been formed into four modules: Optics Module, Spacecraft Module, Deployable Module, and Instrument Module.
- Each module will be a deliverable to I&T, and each will be the responsibility of a prime contractor and/or space agency.
- Each module may be fabricated, assembled, qualified independently of the others.
- Each module has its own project team, schedule, and budget.
- Interfaces between modules will be controlled via the typical ICD process during Phase A/B/C.

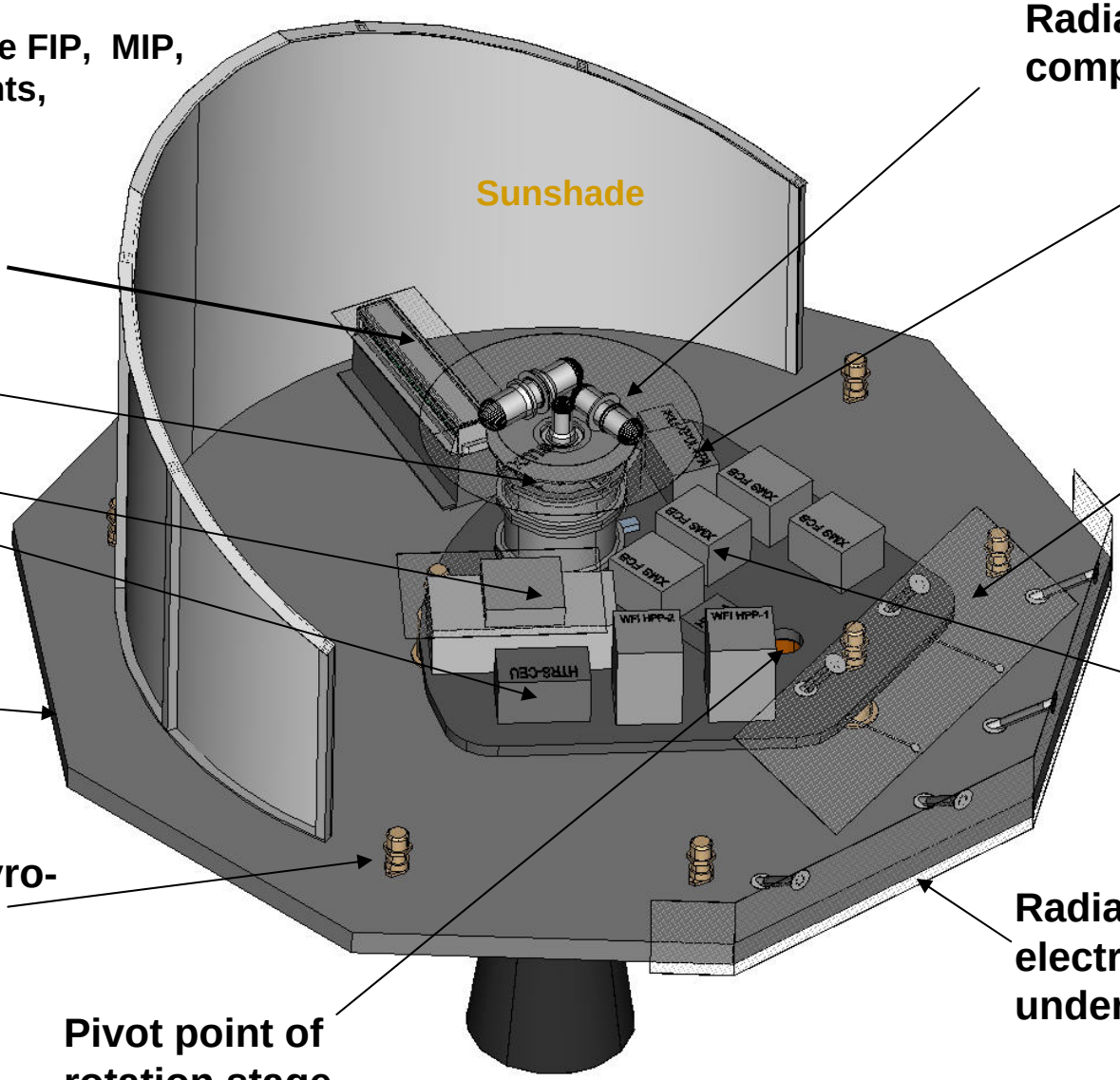
Instrument Module

The IM consists of the following mechanical systems

- Instruments
  - XMS, WFI, HXI, XPOL, HTRS, XGS Camera
- Fixed Instrument Platform (FIP)
  - Platform for MIP, XGS camera, many electronics boxes, sunshade
  - 9-sided 4” thick honeycomb panel, .020” aluminum facesheets
  - Embedded variable conductance heat pipes (VCHPs)
- Moveable Instrument Platform (MIP)
  - Platform for XMS, WFI/HXI, XPOL, HTRS instruments, and ~10 proximity electronics boxes.
  - 2” thick honeycomb panel, .020” aluminum facesheet
  - Embedded VCHPs and Rotation stage between MIP and FIP
- Rotation Stage
- Common baffle attached below FIP
  - Carbon Fiber Reinforced Plastic (CFRP) conical or cylindrical baffle to block stray light
- Several positioning stages for instruments.
  - XMS: focus
  - WFI/HXI: focus
  - XGS: focus and translation
- Radiators and Struts
  - Aluminum honeycomb radiators with embedded Constant Conductance Heat Pipes (CCHPs).
- Sunshade
  - Semicircular CFRP tubular frame with MLI blanket to block sunlight.
- Launch Locks on MIP and FIP

Instrument Module

The IM consists of the FIP, MIP, Sunshade, Instruments, Electronics boxes



Radiator for XMS compressor

XPOL

XGS CCD Camera

XMS

WFI/HXI

HTRS Instrument

Radiator for boxes on Moving Instrument Platform (MIP)

Fixed Instrument Platform (FIP)

Proximity instrument electronics boxes (11)

Launch Locks: pyro-actuated release mechanisms (6)

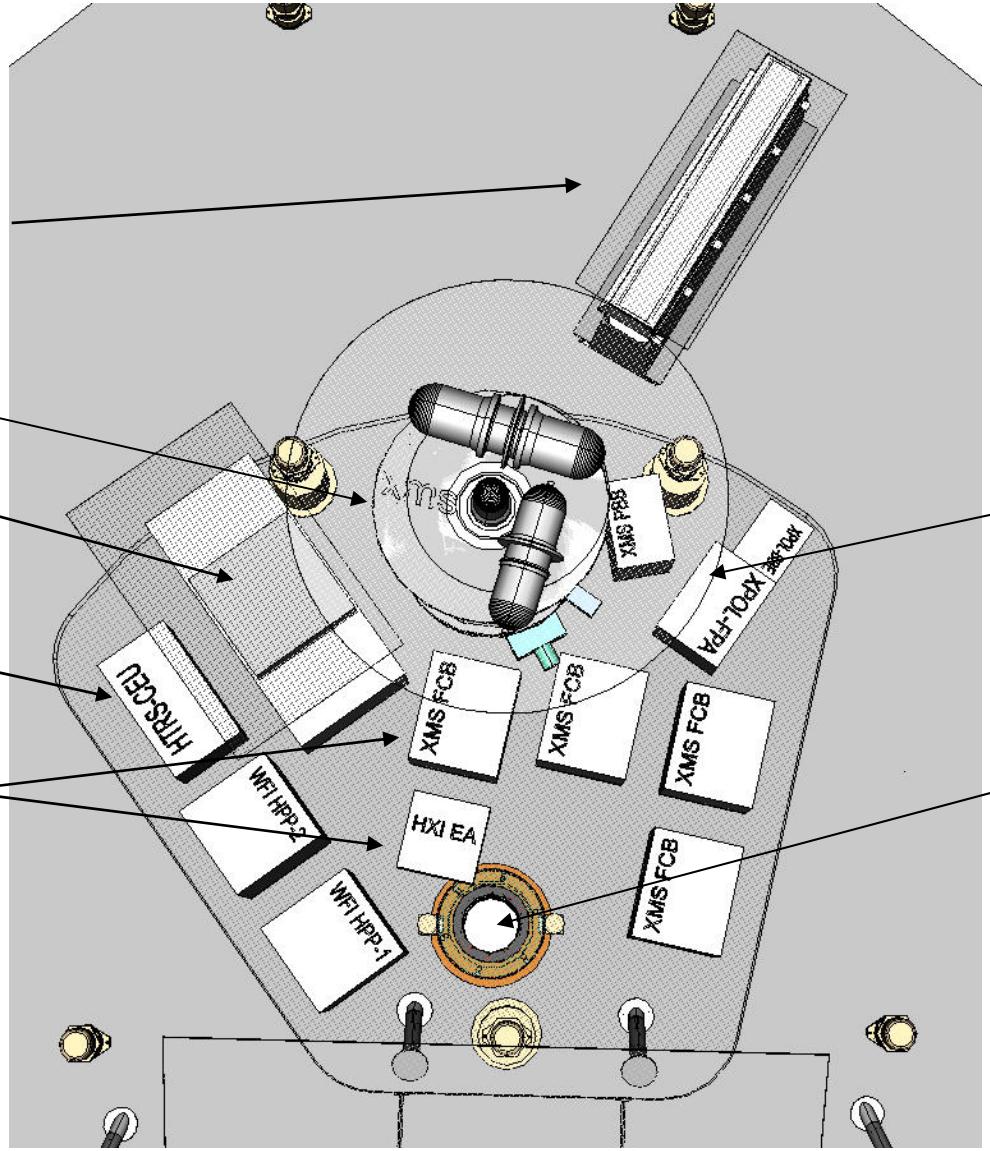
Radiator for electronics boxes underneath FIP

Pivot point of rotation stage

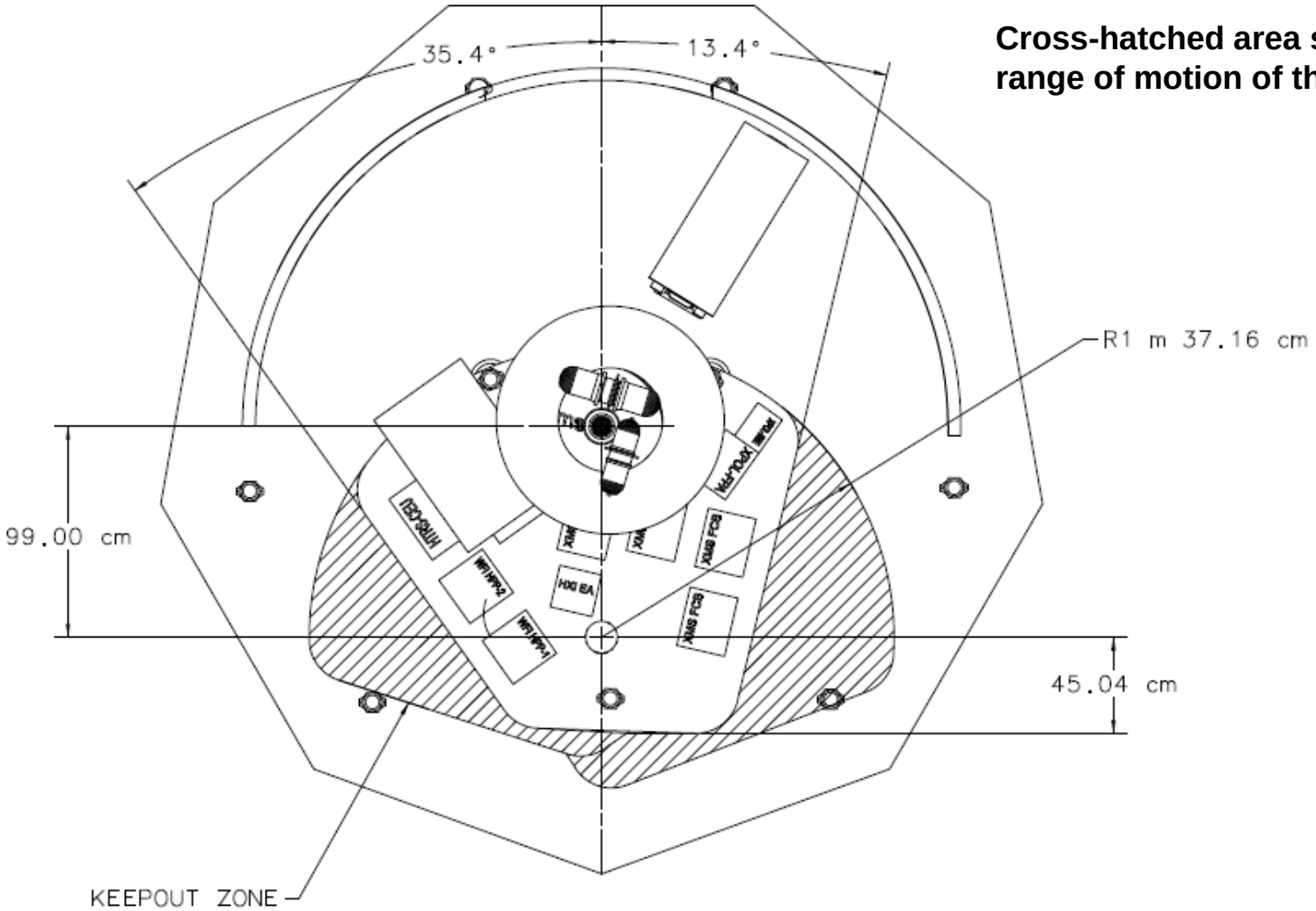
Rotation and Translation Stages

- **Observation plan calls out for several hundred changes between instruments at the focal plane.**
  - **Can't fold an x-ray beam to share the focal plane, so must move instruments in and out of focus.**
- **Traded a linear stage vs. a rotating stage (carousel).**
  - **The distance between 5 instruments side-by-side on the linear platform resulted in excessive translation (~2m) which made harness accommodation difficult, had a large keep out zone, and was heavy.**
  - **Rotating platform eliminated the harness service loop, was lighter, and had a smaller keep out zone.**
- **XPOL, XMS, WFI/HXI, & HTRS are on the Moving Instrument Platform which rotates ± 70 degrees to position each instrument at the focus**
- **All instrument-related wire harness travels through a 15cm hole in the rotational stage and twists along with the platform.**
- **XMS and WFI/HXI require their own focusing mechanisms to compensate for any errors on position due to deployment, thermal expansion or moisture desorption**
  - Max. Allowed On-axis Defocus in Z: +/- .15 mm
  - Focus Mechanism range of motion in Z: +/- 5 mm
- **XGS Camera requires a focus and translation stage**
  - Max. Allowed On-axis + FIP Tilt Defocus in Z: +/- .3 mm
  - Focus Mechanism range of motion in Z: +/- 5 mm

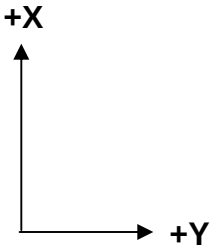
MIP Instrument Suite top view



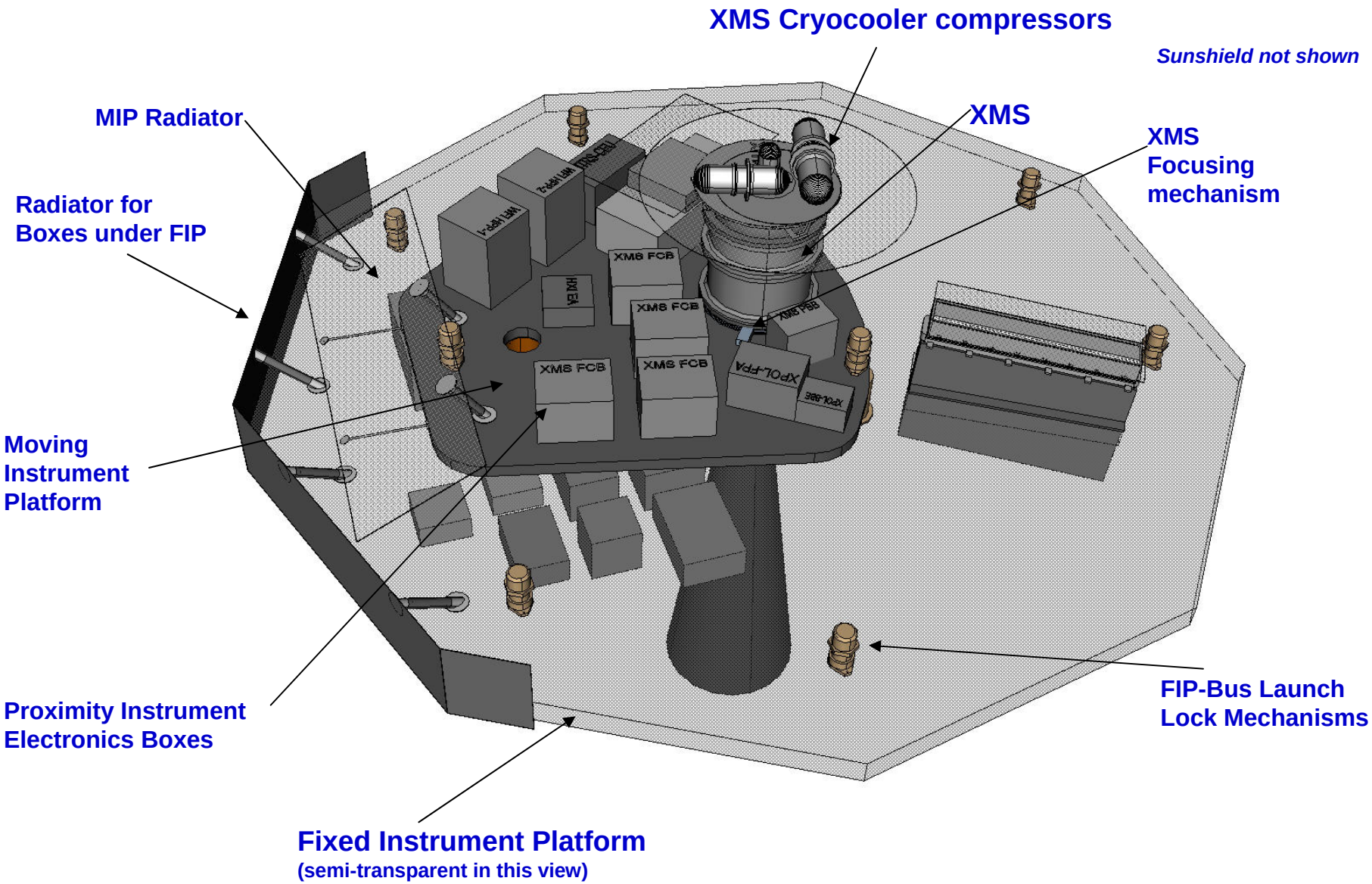
MIP Keep Out Zones



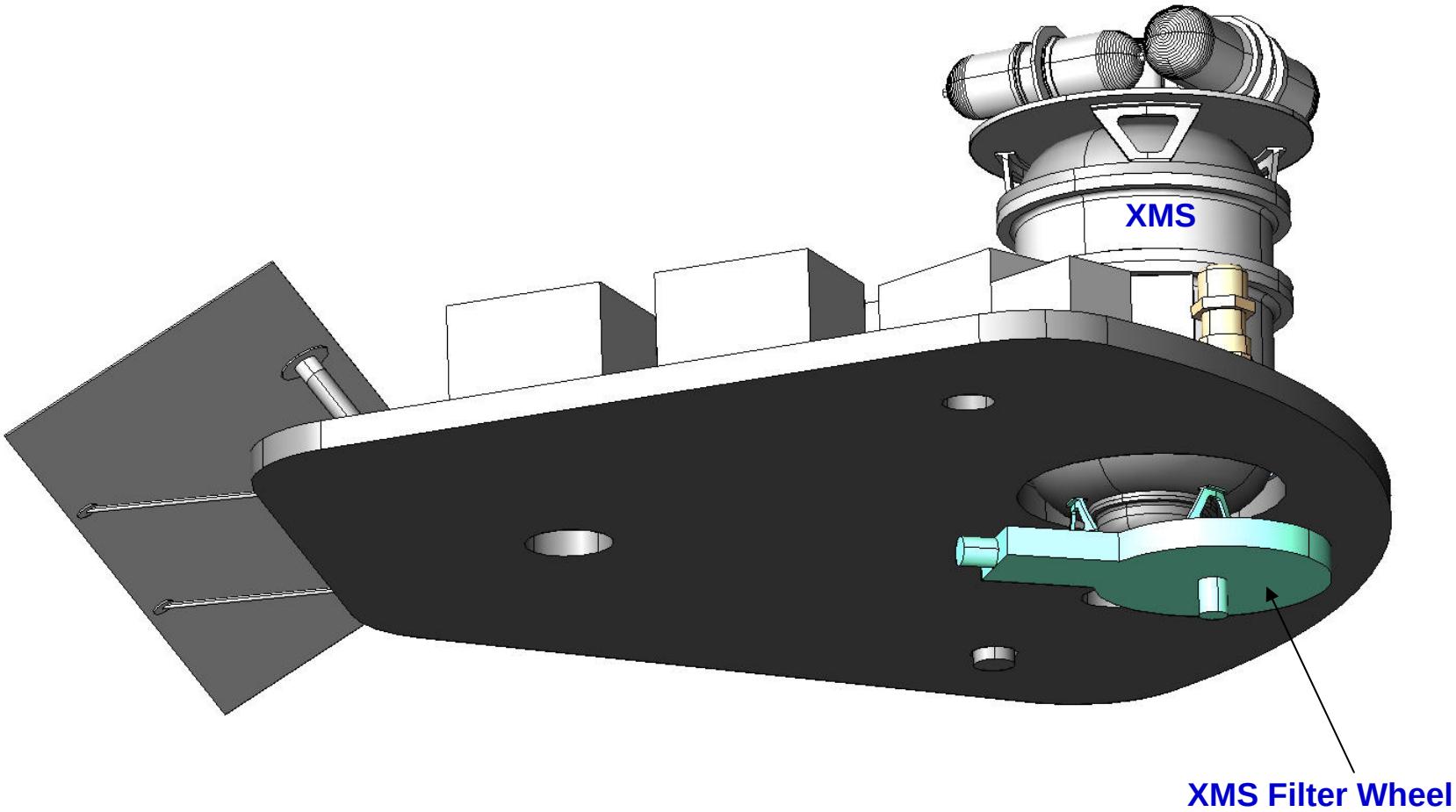
Cross-hatched area shows the range of motion of the MIP.



Instrument Module Side View

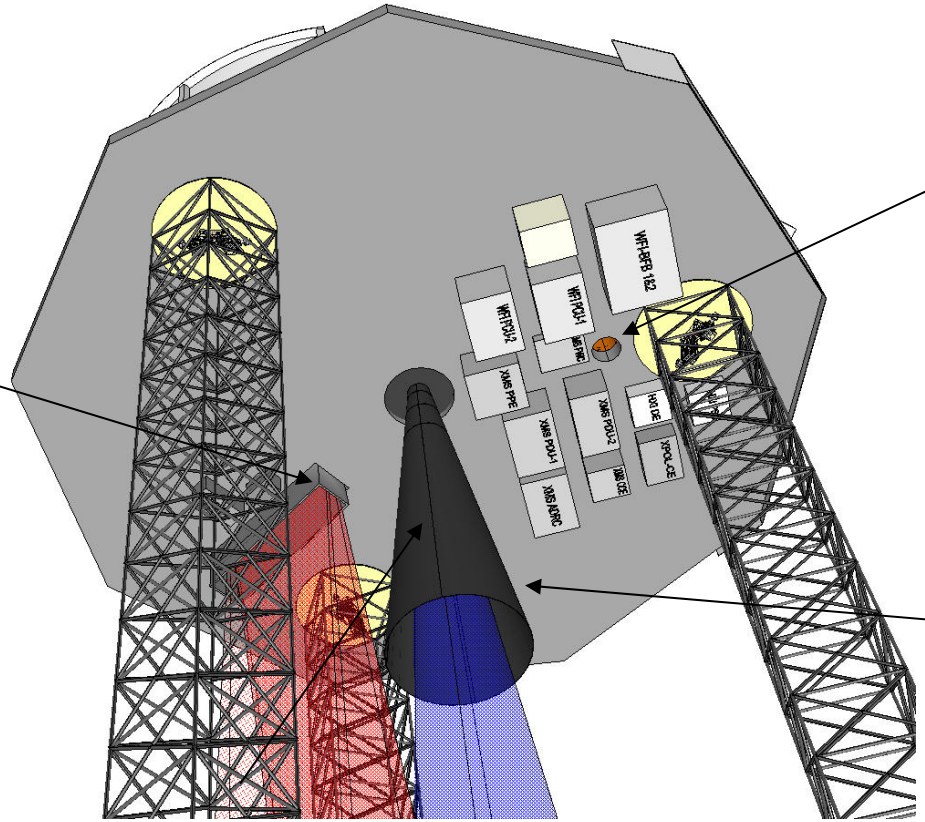


View of XMS Filter Wheel



FIP Underside

- Instrument electronics boxes that do not need to be close to the instruments are mounted on the underside of the FIP.
- Harnesses pass though the 15 cm diameter hole in the rotation stage of MIP.
- Harness from XGS Camera to its electronics box (DEA) travels through a cutout in the FIP.
- 2 meter long “common instrument baffle” for XMS, WFI/HXI instruments



Harness Duct

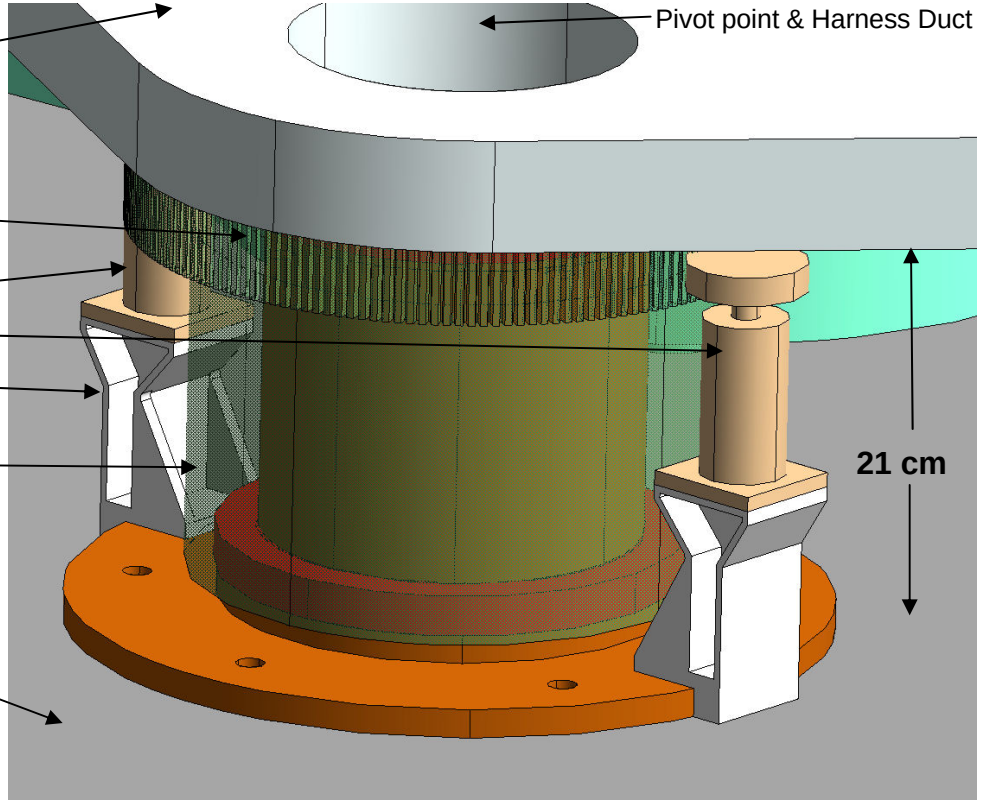
XGS CCD array baffle

Common Instrument Baffle

X-ray beams (blue & red)

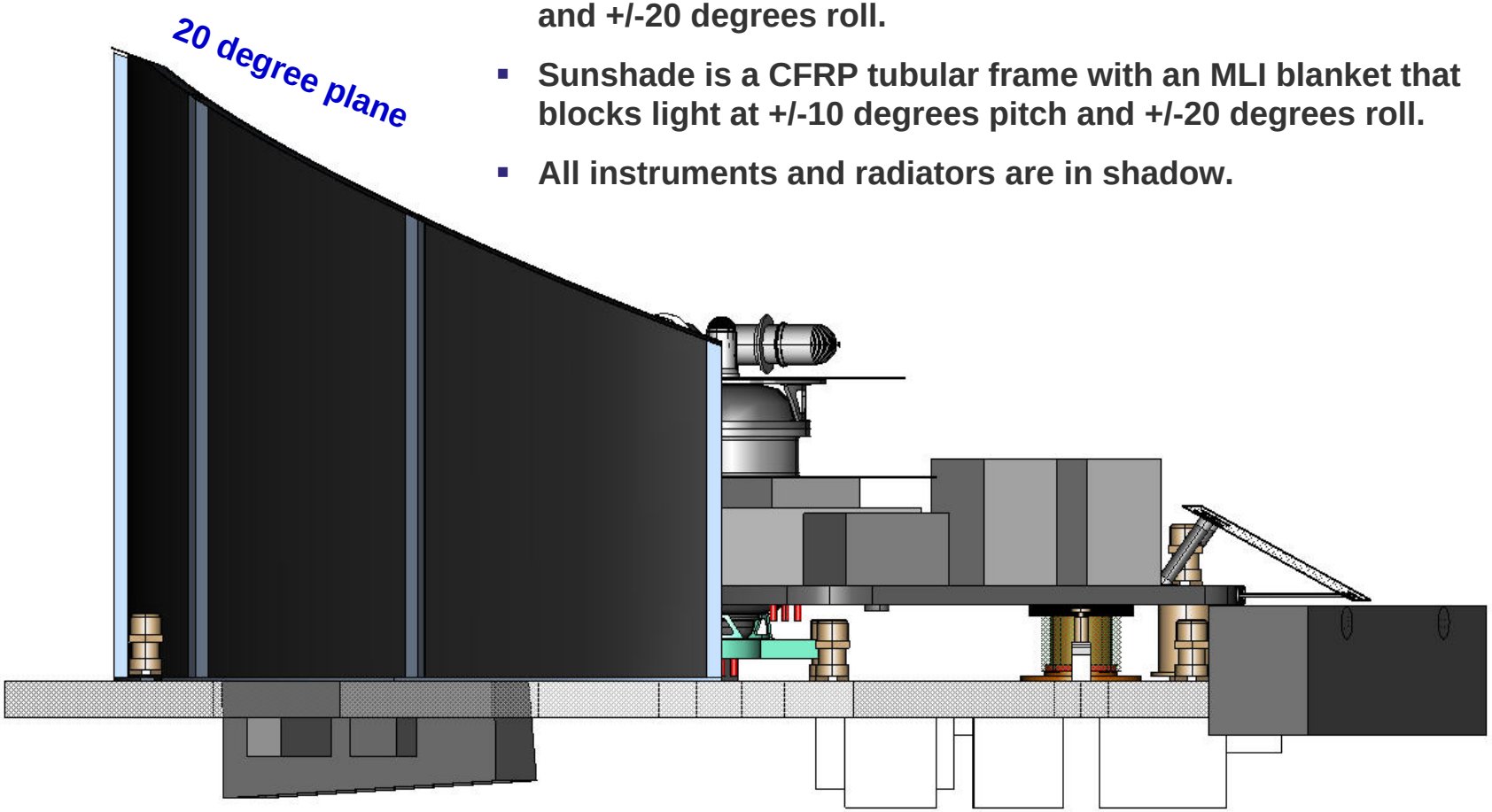
IXO's Rotation Stage

- **Stage consists of a large gear which is driven by two redundant electric motors.**
  - **Stepper motors with encoders.**
  - **Motors have a clutch for engagement/disengagement.**
  - **Motors have the usual redundant windings and controllers, etc.**
- **Mass 10 kg.**



Sunshade

- Observatory pointing requirements are +/-10 degrees pitch and +/-20 degrees roll.
- Sunshade is a CFRP tubular frame with an MLI blanket that blocks light at +/-10 degrees pitch and +/-20 degrees roll.
- All instruments and radiators are in shadow.



Deployment Module

The deployment module consists of the following:

- **Three ADAM masts**
  - ATK (ex AEC-Able) commercial product consisting of a series of longerons, battens, and cross-braces folded inside a canister.
- **Deployable shroud**
  - Two concentric 9-sided MLI blankets stitched in an accordion shape
  - Attached to the shroud are two baffles (.001” Tantalum foil with polymer reinforcement membrane) with cutouts for the x-ray beams.
- **Shroud Stowage Ring**
  - 9-sided CFRP C-channel to hold the stowed shroud
- **Deck**
  - 9-sided 2” thick honeycomb panel onto which the 3 ADAM masts and shroud stowage ring are mounted.

Deployment System Requirements / Goals

- About 12 meters deployment length.
- Must be able to deploy mass/inertia of IM, shroud, harness, and baffles. Therefore, the system must have significant deployment force.
- Must fit inside the Bus when stowed for launch.
- Deployed 1st bending and torsion modes > 1 Hz. Satisfies ACS Karman Filter algorithm. Could go lower if necessary.
- Deployment positioning capability goal is to put the focal point within a sphere of 2mm diameter true position.
  - Additional mechanisms on instruments provide the fine positioning.
- Deployed stability: Varies per degree of freedom. See requirements sheets.
  - Generally sub-millimeter.
- Deployment time: not important, < 4 hours
- Mass: low as possible, < 200 kg desirable.
- Deployment power: within capability of IXO's EPS. Hundreds of watts.

Deployment Method Trade Study

- **Several deployment methods were studied including:**
  - **Multiple (Able Deployable Articulated Mast) ADAM masts from ATK (previously known as AEC-Able) .**
  - **A single "octoADAM" mast of 4m diameter which surrounds the FMA.**
  - **A single thin walled boom (3.4m diameter, 10m long) which could be deployed by several methods**
  - **Multiple small diameter telescoping Booms**
  - **Multiple Coilable Booms**
  - **Multiple Bi-Stem actuators**
- **We concluded that the ADAM mast combined the best stiffness-to-weight, positioning precision, and highest packaging density with flight heritage of any option.**
- **As a further bonus, an upcoming high-energy X-ray mission called Nustar is also using a single ADAM mast for a 10m deployment.**

ADAM Mast Flight Heritage

Applications			
Program	**Customer**	**Technology**	**Application**
IPEX II	JPL	ADAM	Micron-level stability flight experiment
SRTM	JPL	ADAM	SAR antenna deployment
Wide Swath Ocean Altimeter	JPL	ADAM and ESS	Deployable SAR, Fixed-Baseline Interferometer
AstroPhysics Programs	Various	ADAM	Occulter Deployment, instrument and detector separation
NuStar	JPL	ADAM	Deployable X-ray optical bench

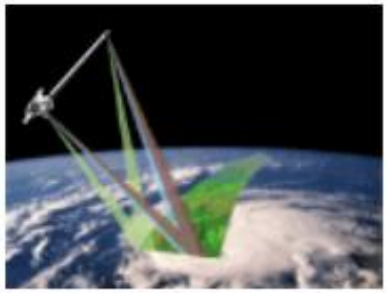
- **International Space Station FAST masts**
  - **35m long, metallic version of ADAM mast. Six currently flying on ISS.**
- **SRTM used a 60m ADAM mast with high deployment accuracy and stability.**
- **Nustar will use an ADAM mast in 2011.**
  - **10 meter deployment length. Mast diameter and components are about 55% size of IXO's ADAM mast. Similar positioning requirements.**
  - **Mast deploys harness approximately equal to its mass. Harness is routed through the mast.**

ADAM Mast on SRTM

Shuttle Radar Topography Mission (SRTM)

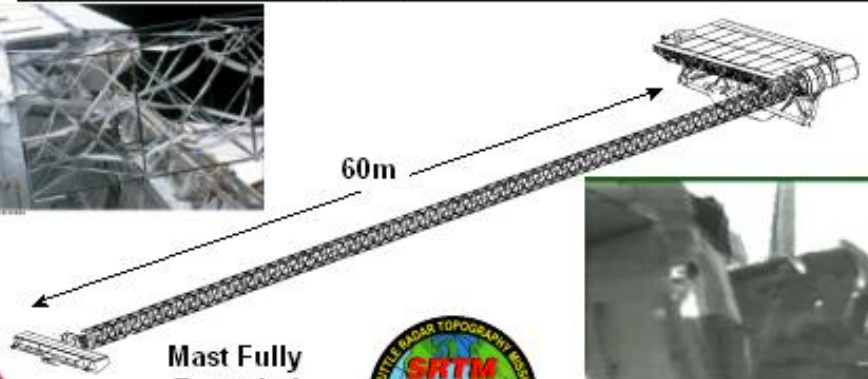
SRTM mapped 80% of the Earth's land mass in a single 11-day Shuttle Flight - February 2000

- Deployed/retracted 400-kg antenna 60-m from the Shuttle Cargo Bay
  - Including ~200-kg of electrical harnesses, coaxial & fiber optic cables along the length of the mast
  - Validated extreme stability and precision of ADAM technology



Measured Deployment Accuracy (Repeatability @ 60m)

Length	<± 1.3 mm (from +66C to -60C)
Tip Translation in Shear	< ± 0.25 mm
Tip Twist in Torsion	< ± 0.02°
Tip Rotation in Bending	<< ± 0.005°



ATK ABLE

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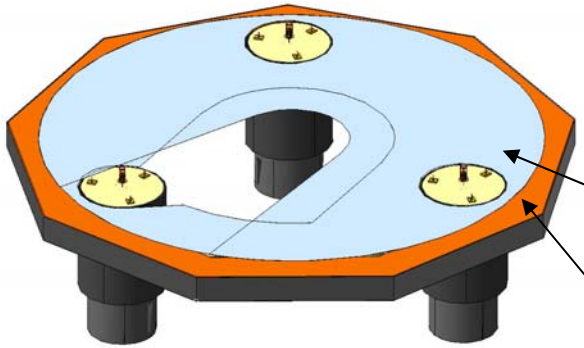
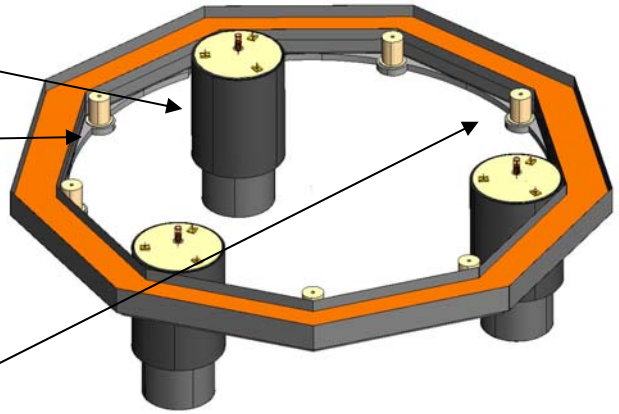
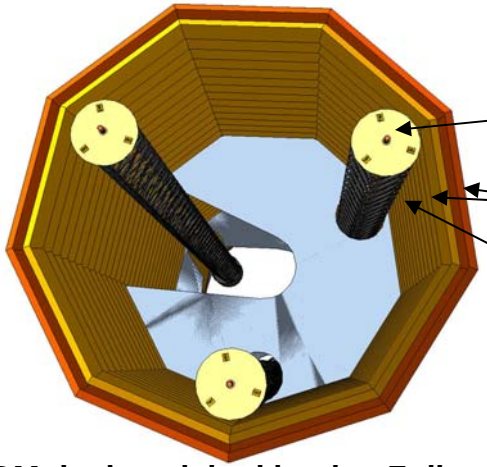
Deployment Module Implementation

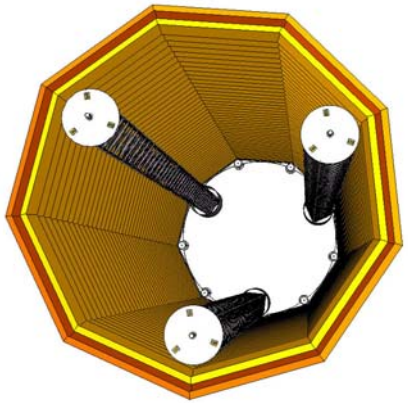
- 3 ADAM masts deploy the IM a distance of 11.9 meters.
- Masts stow into canisters 65cm diameter, 1m long. **Canisters are located on a circle 2.87m diameter.**
- Harness, shroud, and baffles are pulled up by the ADAM masts.





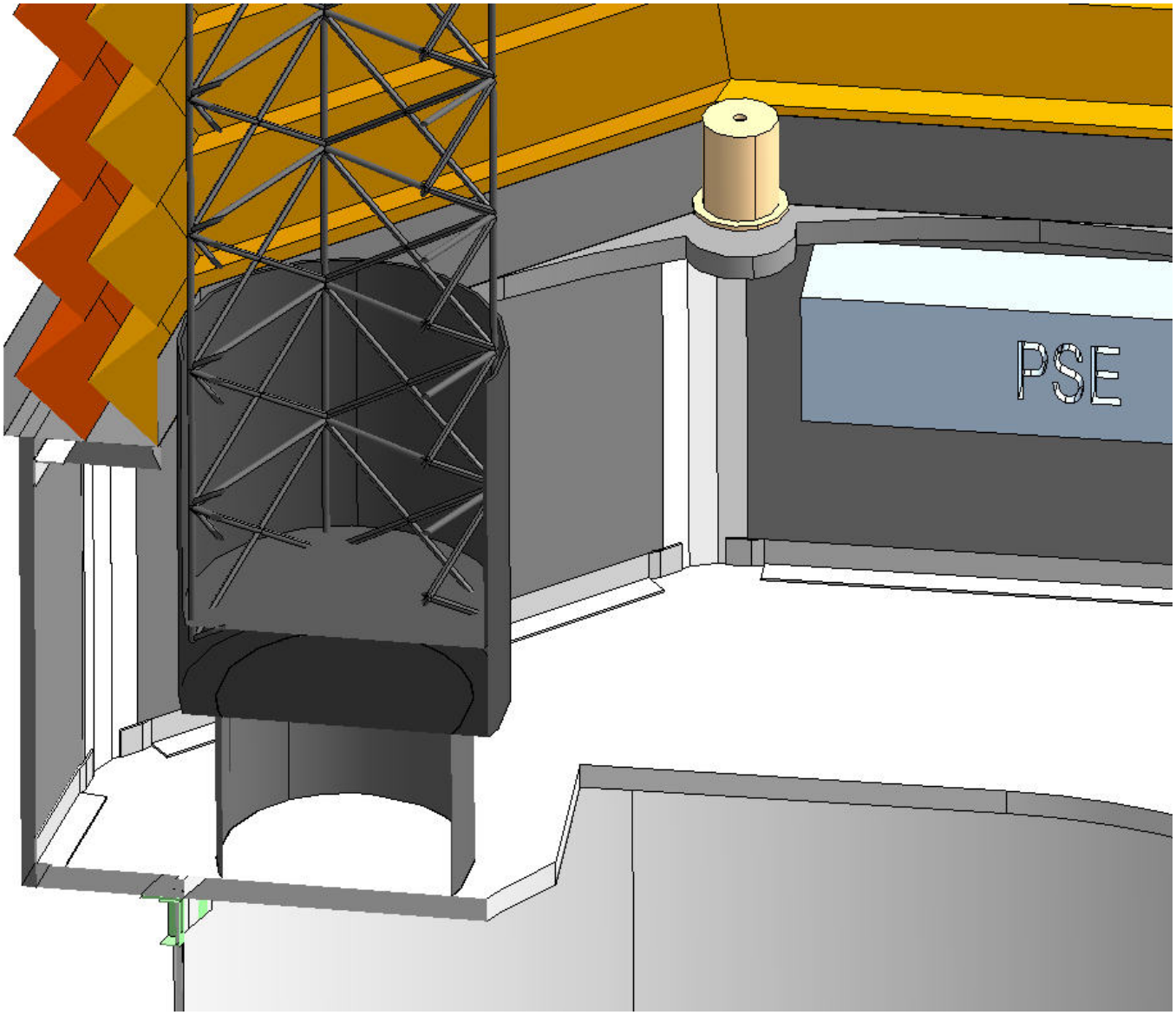


DM deployed, looking in +Z direction



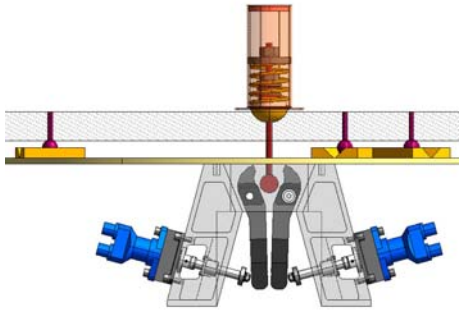
DM deployed, baffles removed for clarity

Interface between Deployment Module and Spacecraft Module

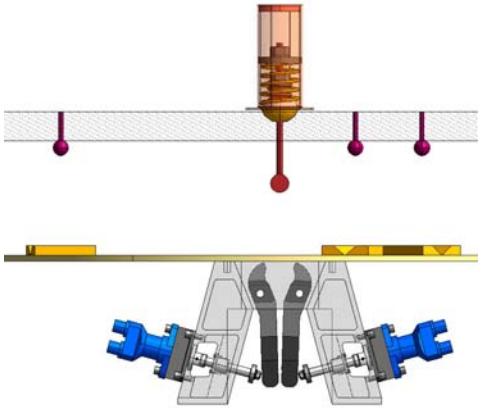


Instrument Module Interfaces to Deployment Module

- The deployable shroud is fastened around the perimeter of the FIP
- IM interfaces with the Deployment Module (DM) where the three ADAM masts are attached to the FIP
- When stowed, six pyrotechnic launch lock restraint mechanisms secure the FIP to the Deployment Module.
- The FIP-Mast joint can be a capture latch mechanism which could allow the mast to be disconnected from the FIP in case of a mast failure.



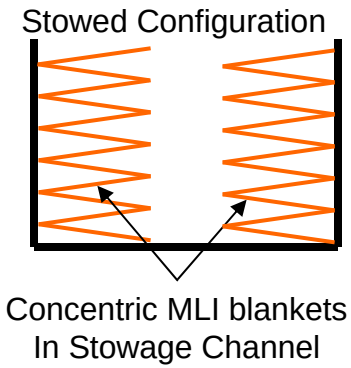
Latch jaws open

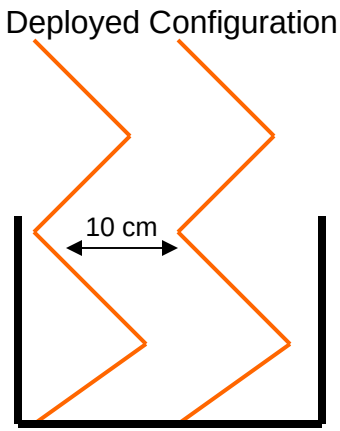


FIP is disconnected from failed ADAM mast

Shroud Subsystem

- Shroud is necessary to block light from entering instrument apertures.
- Shroud assembly consists of two MLI blankets which are pleated like an accordion or camera bellows.
- Pleats allow the shroud to be folded up into a channel located on top of the spacecraft bus for stowage
- Two concentric blankets separated by 10 cm form a "Whipple shield" which reduce micrometeorite penetrations from thousands to ~35.
- MLI is 5 layers of ¼-mil aluminized Mylar and Dacron scrim cloth with 2-mil Kapton inner and outer layers. Innermost layer is black.
- Combined mass of the shrouds is 127 kg.





Shroud Prototypes

- To verify the deployable shroud TRL, the GSFC Blanket shop created a 1/25th scale prototype, and a full scale section.
- Scale shroud stows to 3.5cm with some compression force and extends to 49cm nominally.
- Full-scale 4-pleat section shows that the shroud can stow in < 20cm height.

Flight Example : Hubble's ESM Accordion Blanket

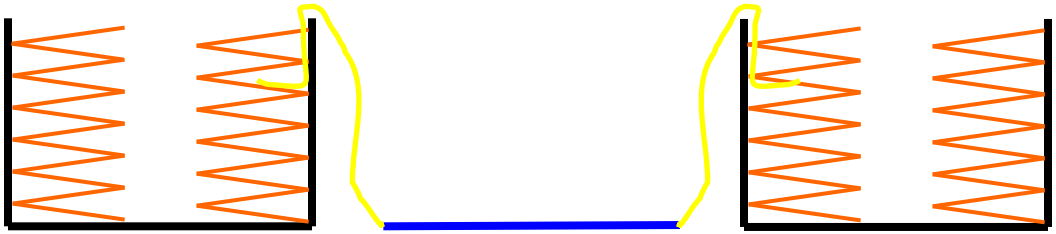
- Accordion-style blanket made for HST Electronic Support Module (ESM) on STS-109 (March 2002). This blanket protected the ESM in the shuttle bay and was deployed & retracted by an EVA astronaut.
- 5" tall when compressed, expands to 42" tall. Fully stretched length of MLI is 68"
- Approximate size is 42"x36"x3"

Baffle Interface to Shroud

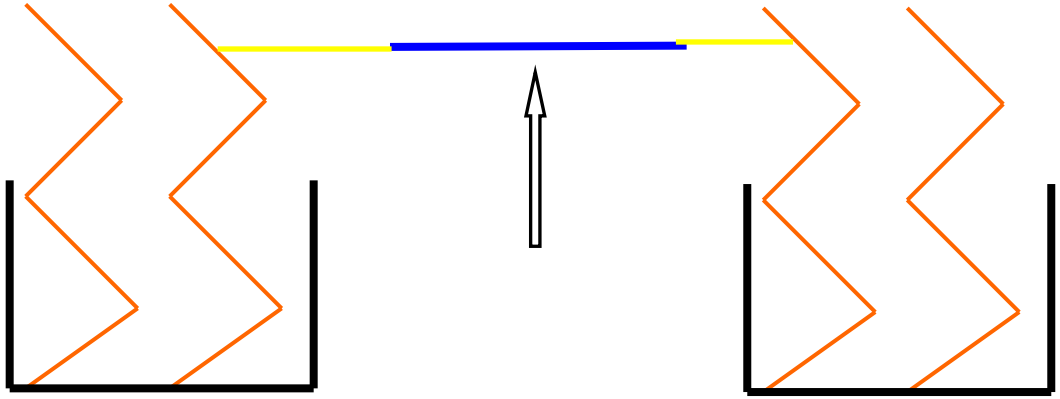
Baffles deploy with the shroud

- Attached via thin wires or Kevlar strings to the appropriate pleat of the shroud

- **No direct interface to the masts**



Stowed configuration



Deployed configuration

Accommodating Harness in the Masts

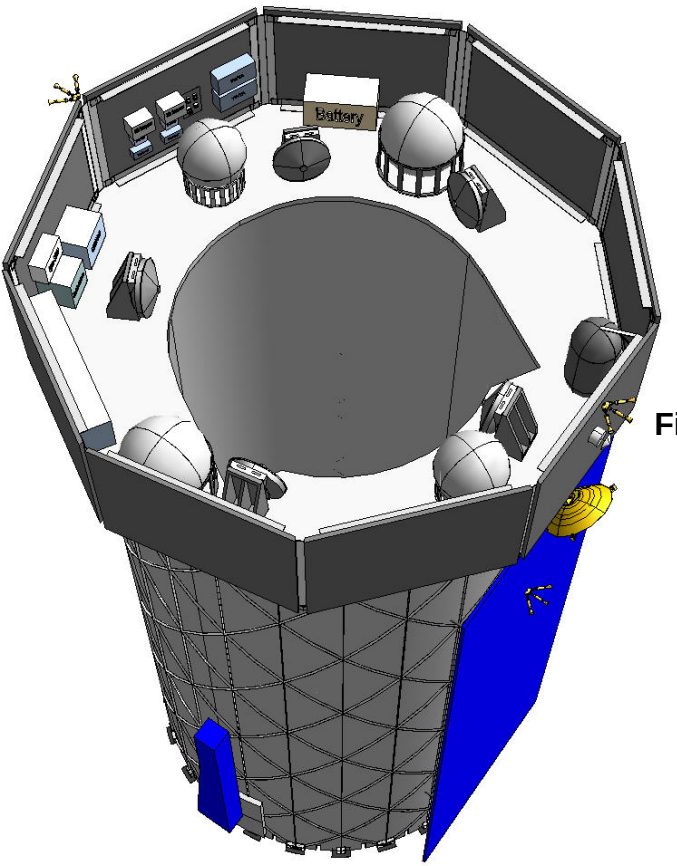
- There will be harness between the instrument module and the spacecraft module. Redundant services A & B.
- ~75 kg harness between IM and Bus on the anti-sun mast and 37.5kg harness on the other two masts.
- Wire harness will thread through the masts similar to the SRTM and Nustar missions.
  - SRTM's harness weighed more than the ADAM mast. Nustar's harness weighs same as the ADAM mast.
- Backup option: harness could be on separate reels between the IM and the Bus.

Spacecraft Module

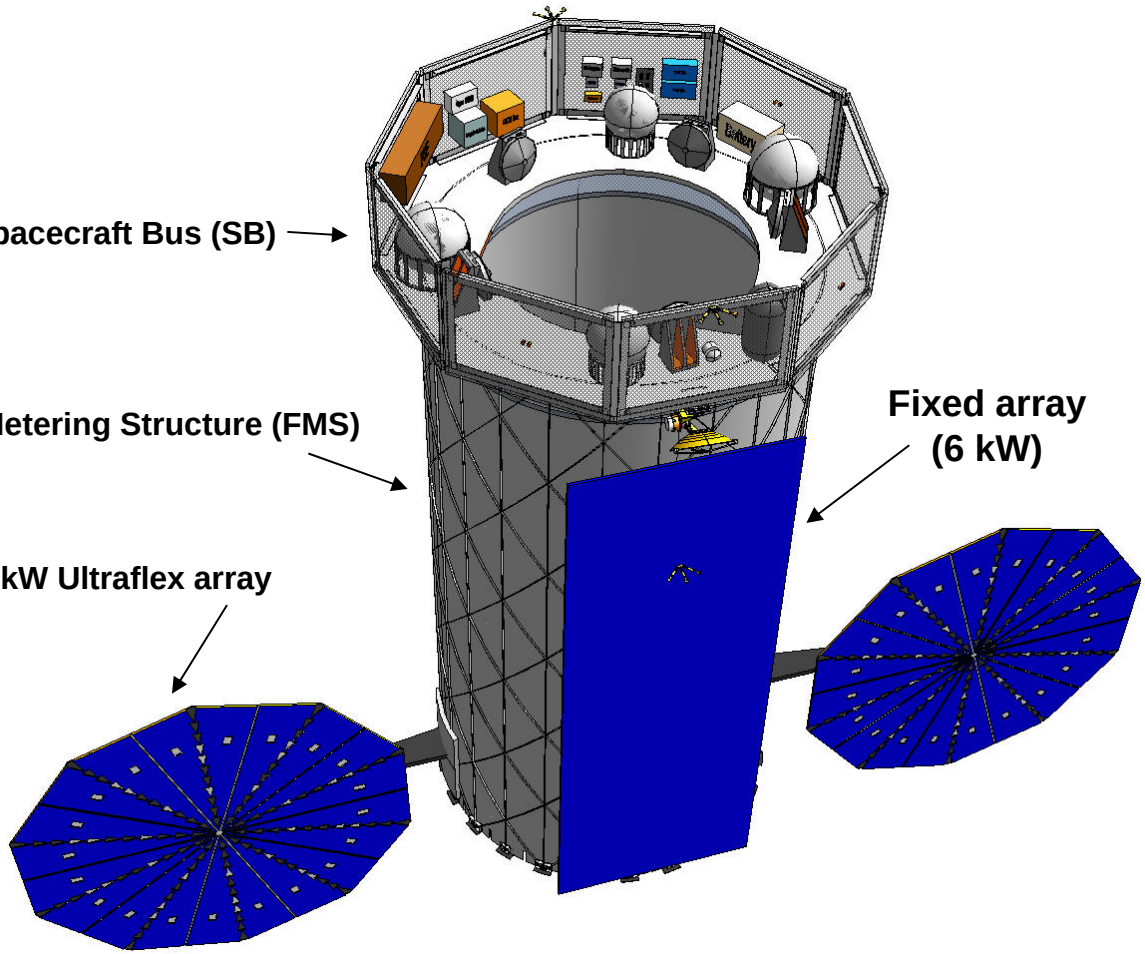
The Spacecraft Module (SM) consists of the following:

- Spacecraft Bus (SB)
  - 9-sided volume with honeycomb panels and CFRP framework
- Fixed Metering Structure (FMS)
  - Advanced Grid Stiffened CFRP cylinder
- Avionics
  - PSE, Battery, C&DH, transponders, Reaction wheels, gyros, etc.
- Harness
- Propulsion system
  - Bi-prop system with 2 fuel, 2 oxidizer tanks, 1 He Pressurant tank
  - 8 thruster triads
  - 2 1N solar pressure torque offload trim thrusters (primary and backup)
- Solar Arrays
  - One 11.5m^2 fixed array on FMS, 2 3.9m diameter deployable Ultraflex solar arrays
- Antennas
  - 1 Ka-band 0.5m diameter antenna on azimuth & elevation gimbals
  - 2 S-band Omni antennas

Spacecraft Module Views



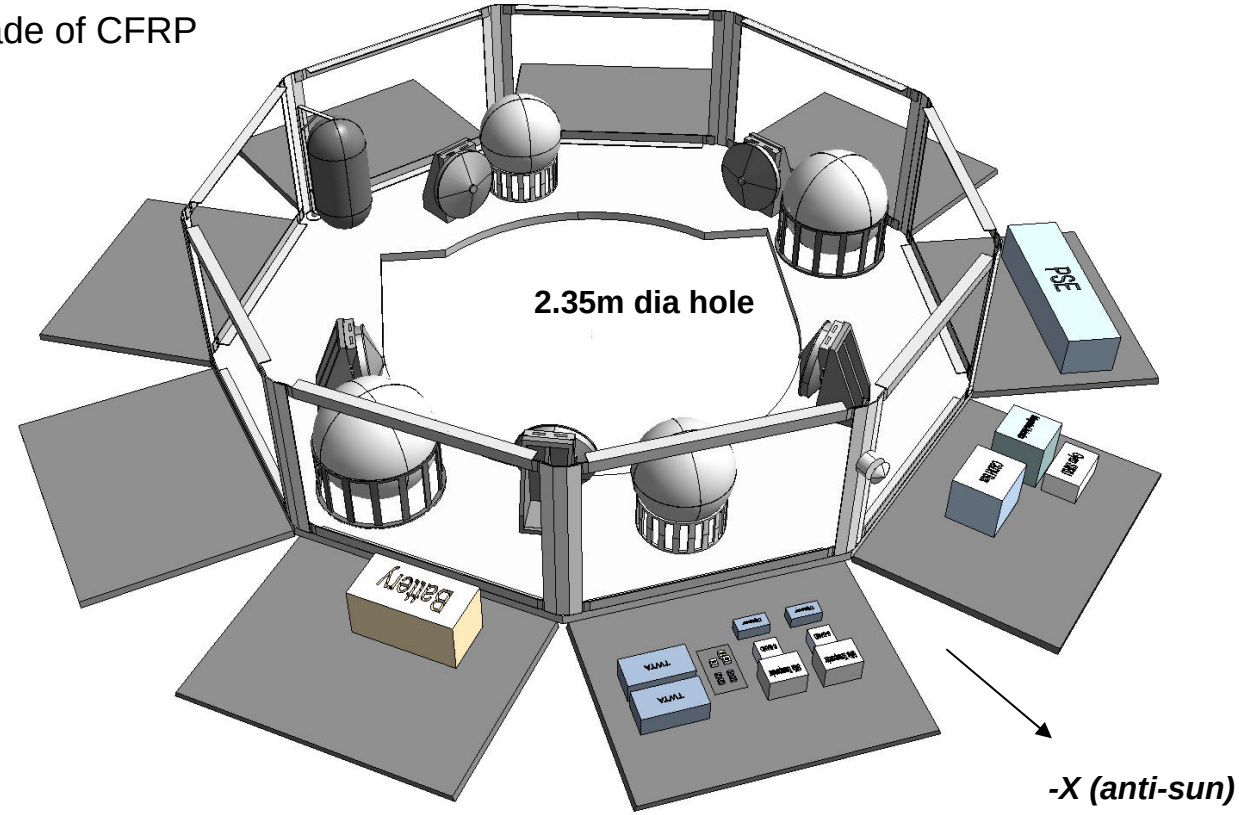
Stowed configuration



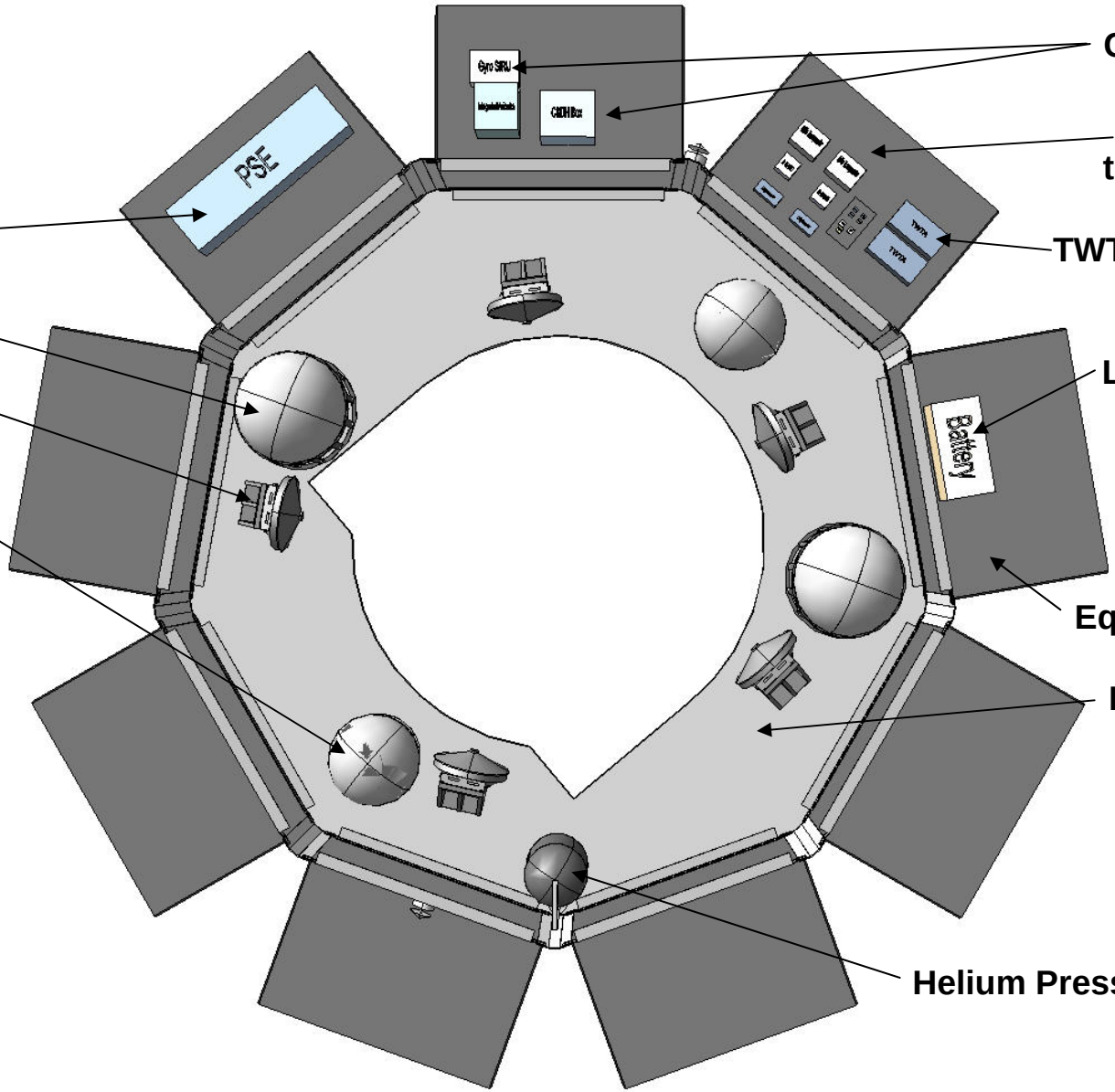
Deployed configuration

Bus Module Description

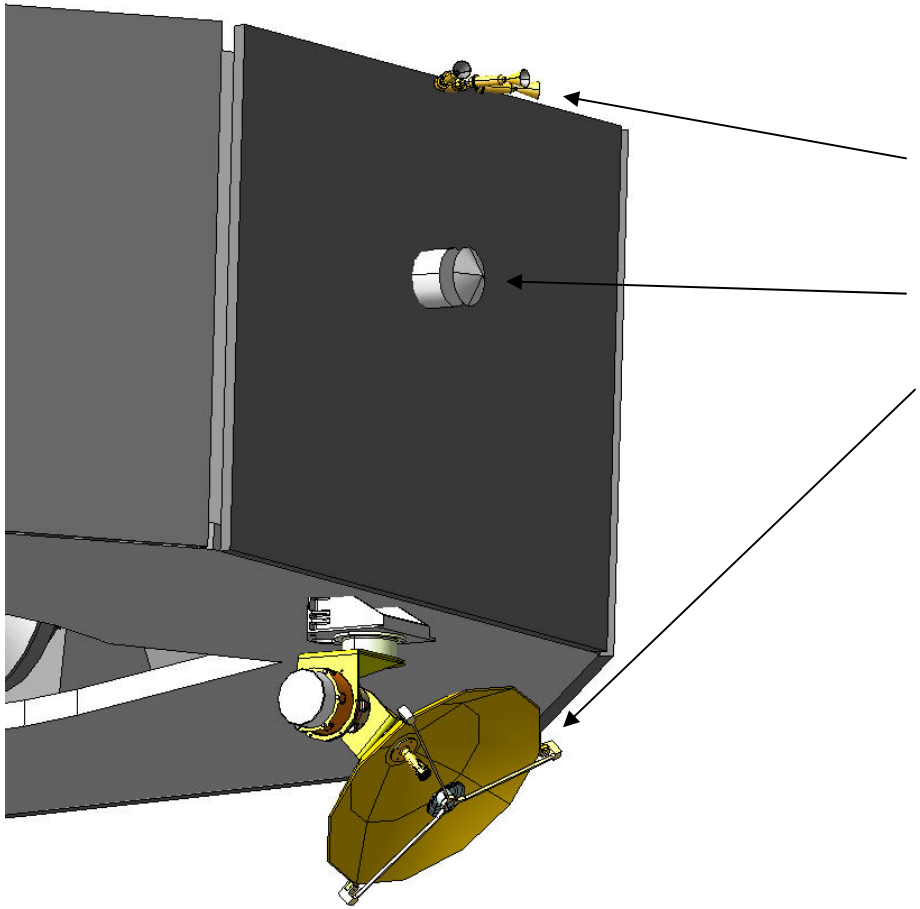
- Bus is 9-sided to allow symmetric placement of 3 ADAM mast canisters.
- Avionics are mounted to the 4 anti-sun panels so they may radiate heat to deep space.
- Propulsion tanks oriented symmetrically around centerline to miminize drift of CG as propellant is consumed.
- 2.35m diameter hole in bottom deck is for the FMA X-ray cone and XGS grating x-ray beams.
- Equipment panels made of CFRP honeycomb panels (graphite facesheets, 5052 aluminum core).
- Bottom deck has aluminum facesheets and embedded CCHPs to reduce thermal gradients.
- Frame made of CFRP



Bus Layout


Gyro SRU
C&DH Box
PSE
TWTA
TWTA
Battery
C&DH, Gyros
S-band transponders
TWTAs for Ka-band system
Li-Ion Battery
Equipment panel
Bottom deck
Helium Pressurant tank
PSE
Hz Tank (2)
Reaction Wheel & bracket (5)
Oxidizer Tank (2)

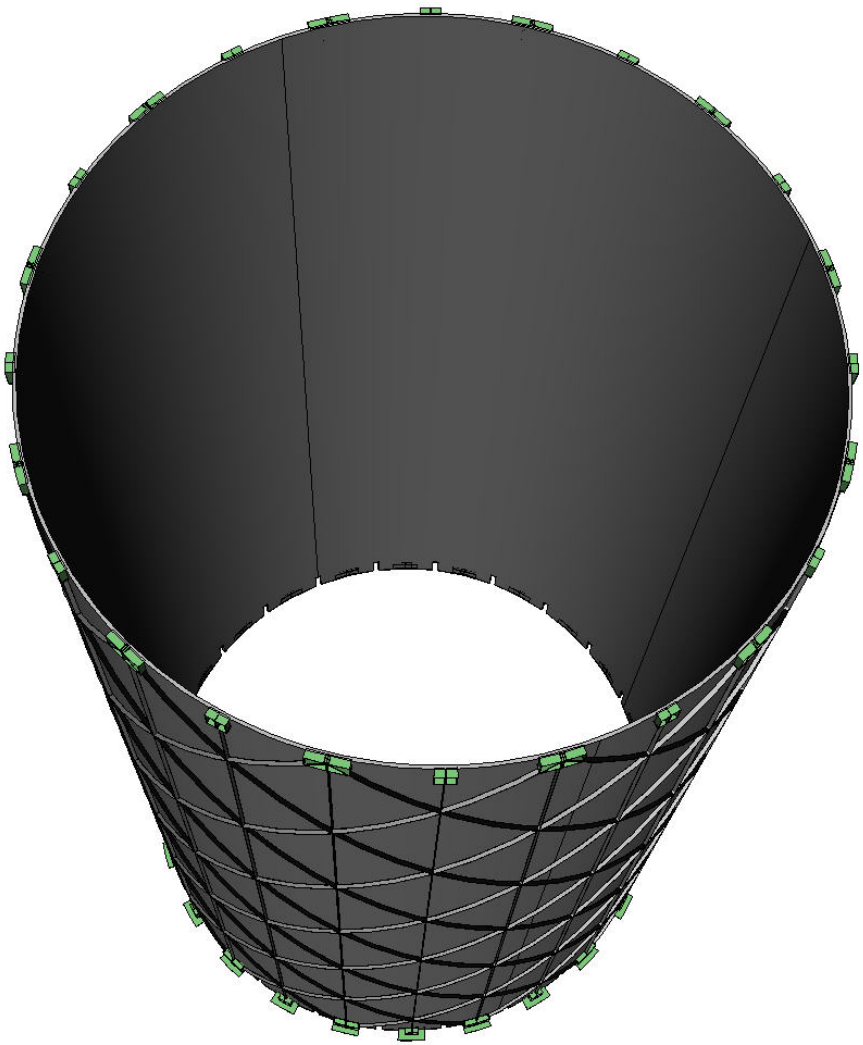
Antenna and Thruster Detail



- Thruster Triad is located at highest point on Bus panel
- Omni antenna on the +X and –X sides
- Ka-band antenna has an azimuth and elevation gimbal. 0.5m antenna

Fixed Metering Structure (FMS)

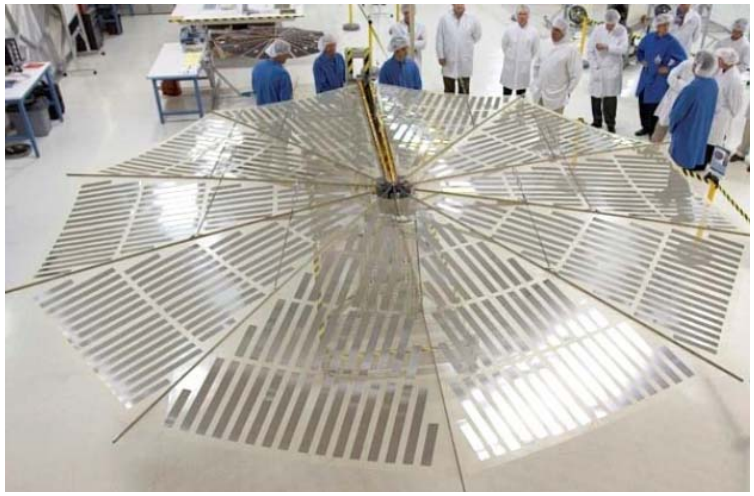
- FMS provides 6.7m spacing from the FMA, support structure for the solar arrays and thrusters.
- CFRP cylinder consisting of a thin skin (1.5mm) with vertical longerons and spiral rib stiffeners 6mm wide, 38mm tall.
  - Advanced Grid Stiffened geometry (isogrid)
- M55J/954-3 composite in quasi-isotropic near zero-CTE layup.
- Made in one piece via Automatic Fiber Placement Machine.
  - similar to Boeing 787 Dreamliner fuselage
- Titanium end fittings are bonded to top and bottom perimeter.
- Mass is 312 kg including end fittings



Ultraflex Array Heritage and Deployment Video

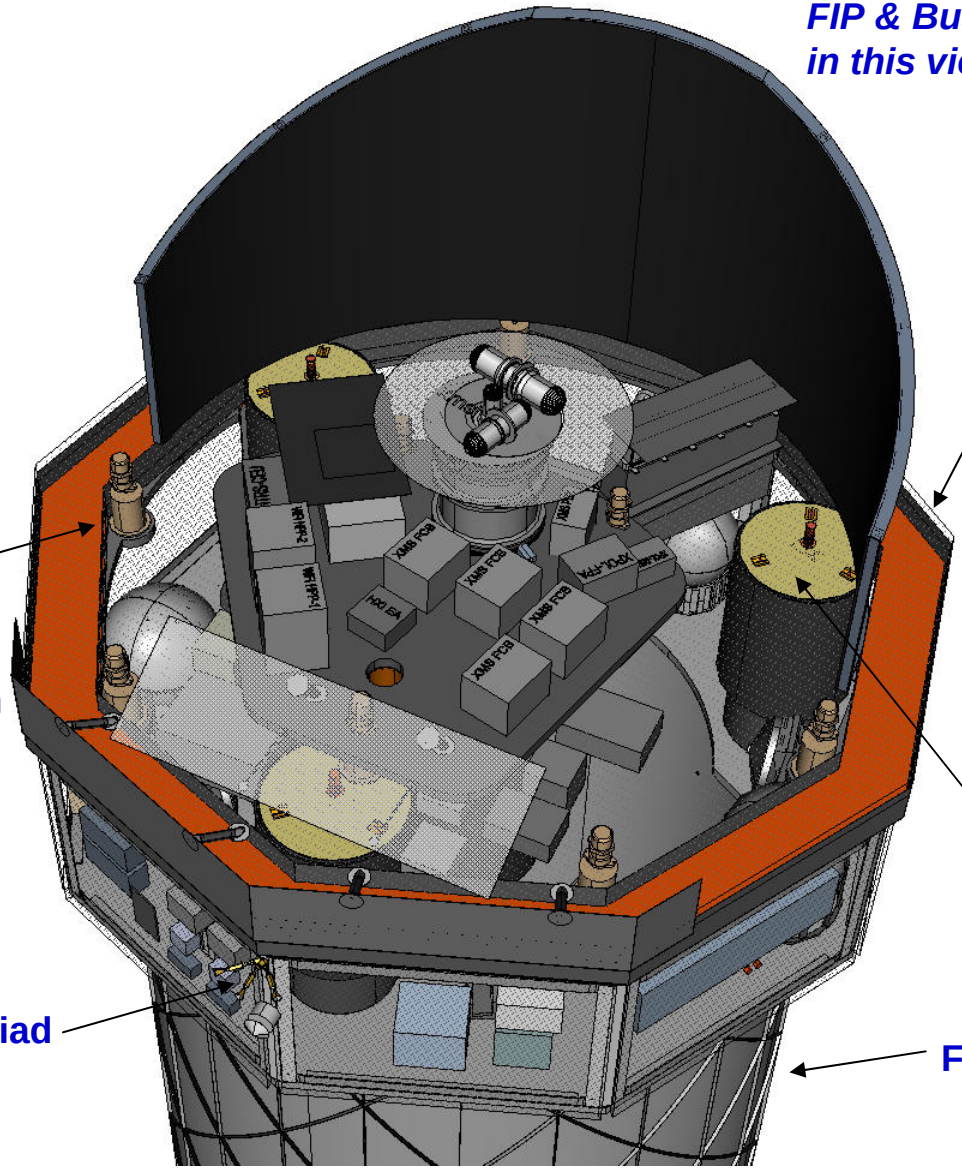
ST-8 Project
ETU Ultraflex Array

Mars Phoenix Lander
Ultraflex Array



Orion Project
ETU Ultraflex Array
(5.5m dia)

Stowed IM, DM, and SM



FIP & Bus Panels are semi-transparent in this view

~4m diameter Shroud Stowage Channel contains the shroud

Launch locks secure the Instrument module to the Bus for launch

Baffles are not shown in this view but reside under the FIP and are connected to the shroud

ADAM mast interface to the FIP

22N thruster triad

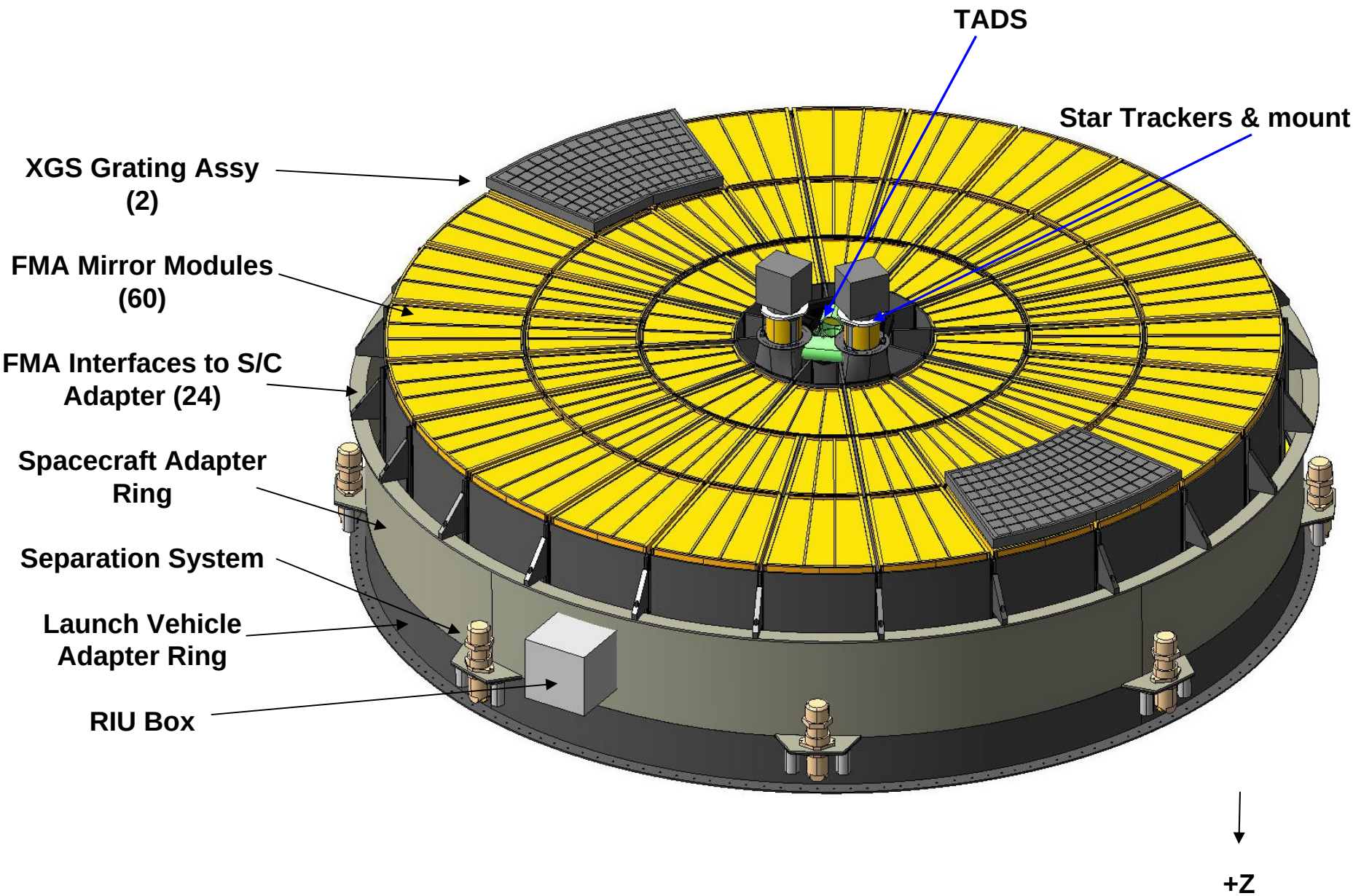
Fixed Metering Structure

Optics Module (OM)

The OM consists of the following:

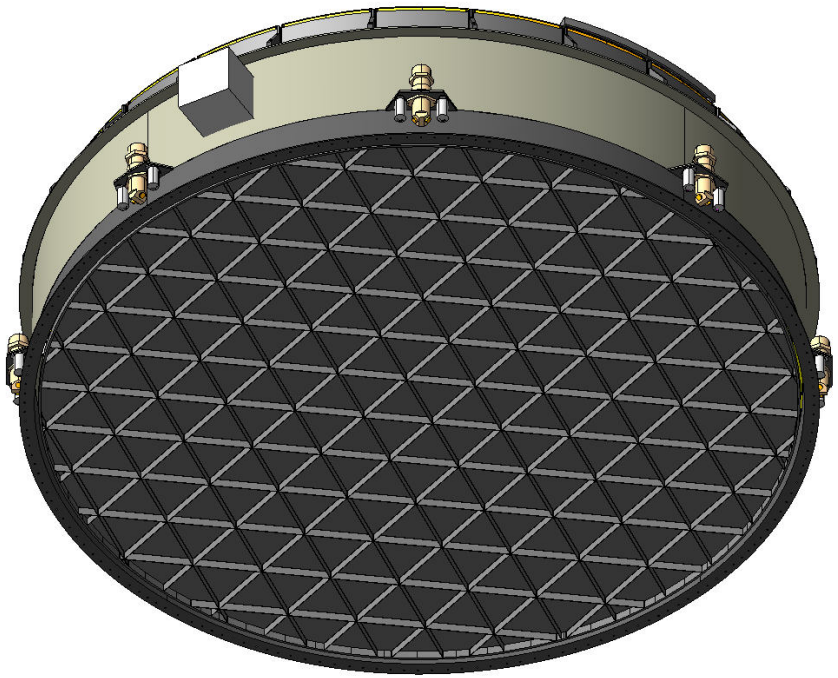
- **Flight Mirror Assembly (FMA)**
  - ~1750 kg glass & CFRP assembly, 3.3m diameter, 80 cm tall
  - HXMM installed in center of FMA
  - X-ray Grating Spectrometer assemblies (2) covering 2 outer modules each
- **Telescope Alignment and Detection System (TADS)**
  - Mounted to inner hole of HXMM. Provides knowledge of focal plane – to – FMA position for x-ray image reconstruction.
- **2 Star Trackers**
  - LMMS AST-301 trackers mounted to inner ring of FMA and interface to the TADS.
- **Spacecraft Adapter Ring**
  - 3.4m diameter 7075 aluminum ring with CCHPs bonded to inside wall minimize thermal gradients
- **Launch Vehicle Adapter Ring and Separation System**
  - 3.4m diameter 7075 aluminum ring with 8 pyro-activated separation nuts and springs to separate IXO from the launch vehicle truss adapter
- **Deployable Sunshade**
  - 1.8m tall, 3.4m diameter semi-circle. Inflatable or pop-up deployment
- **RIU Electronics Box**
  - Heater controller cards, power distribution
- **External FMA Cover**
  - CFRP isogrid cover jettisoned with springs and low-shock release system.
- **Internal FMA Cover**
  - TBD. Requirements under development

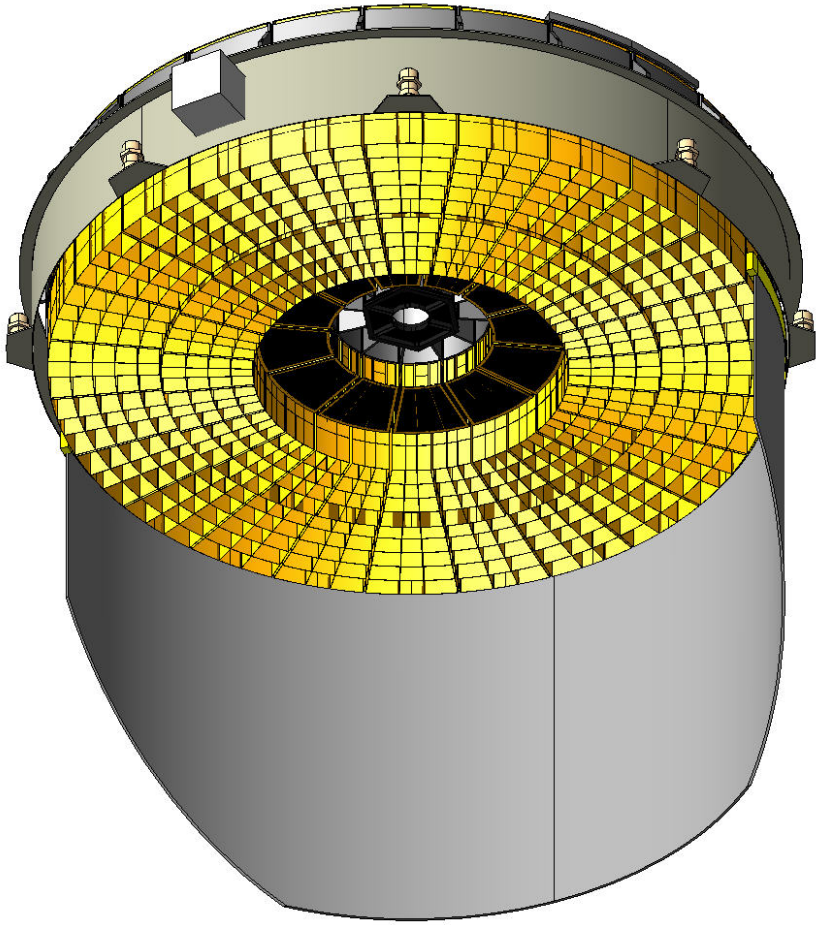
Optics Module Aft End



Optics Module Fore End

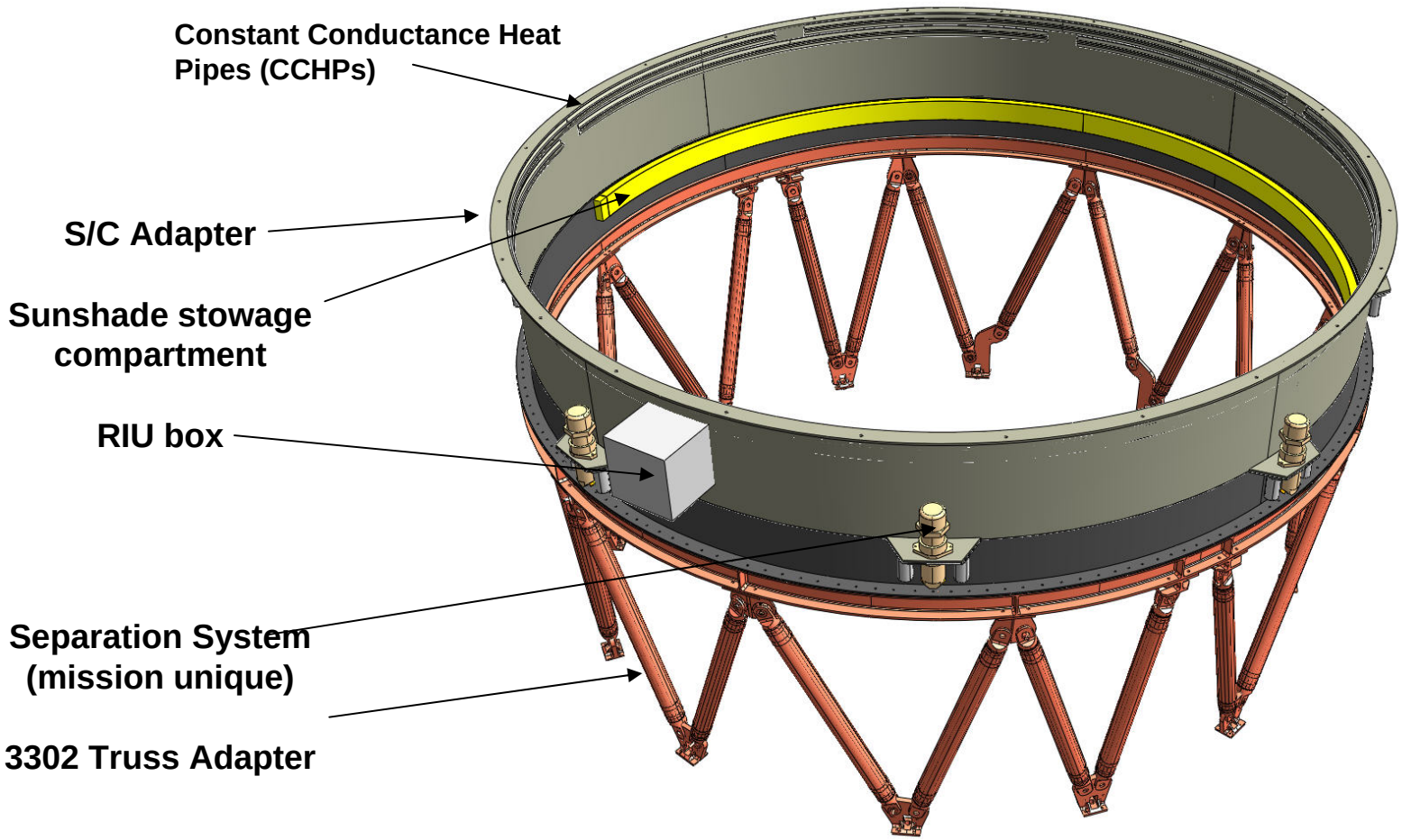
- **Isogrid cover is jettisoned after launch**
- **Sunshield is deployable.**
  - **Inflatable system proposed by L'Garde Inc. weighs ~2.8kg.**





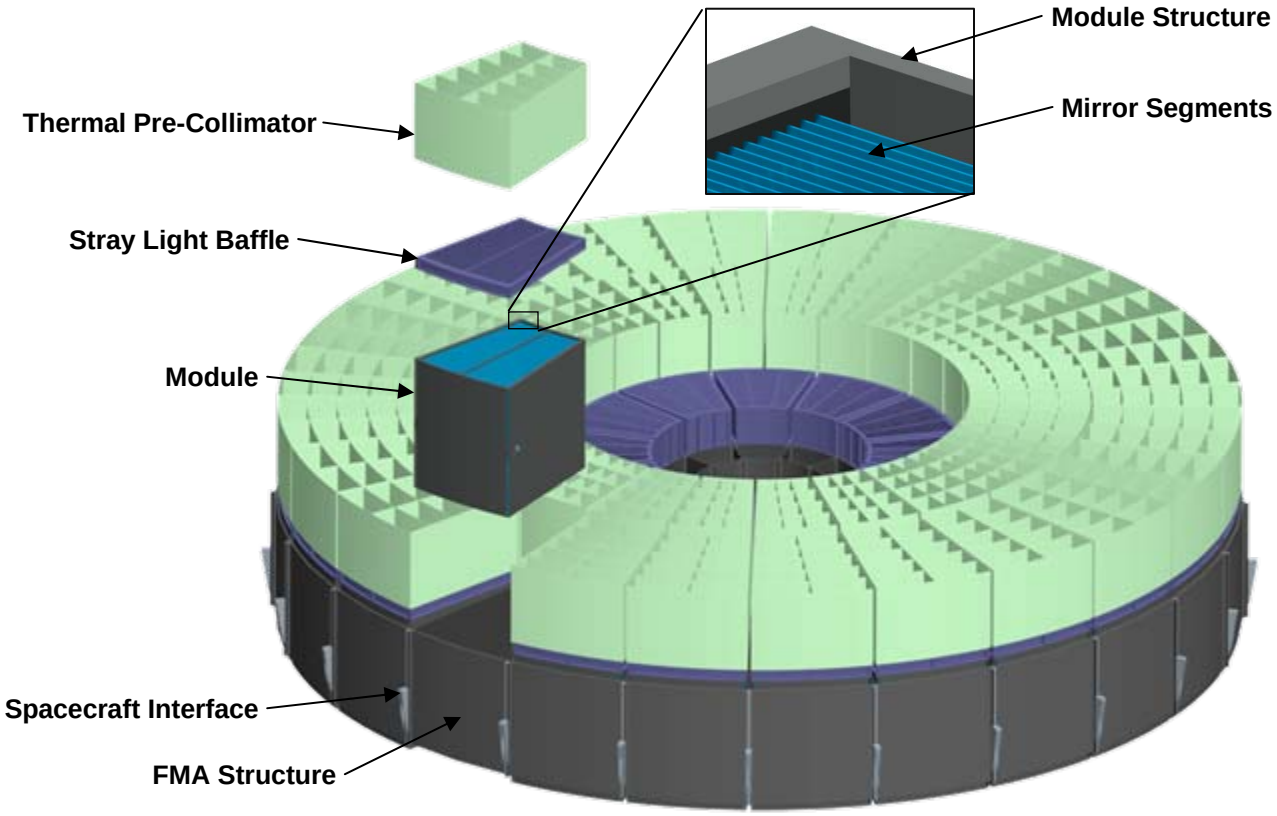
OM Interfaces to Launch Vehicle

- Launch Vehicle Adapter (LVA) bolts to 3302 Truss Adapter
- LVA attached to Spacecraft Adapter via 8 sep-nuts
  - ½" bolt NSI-actuated Sep-nut release system with push-off springs



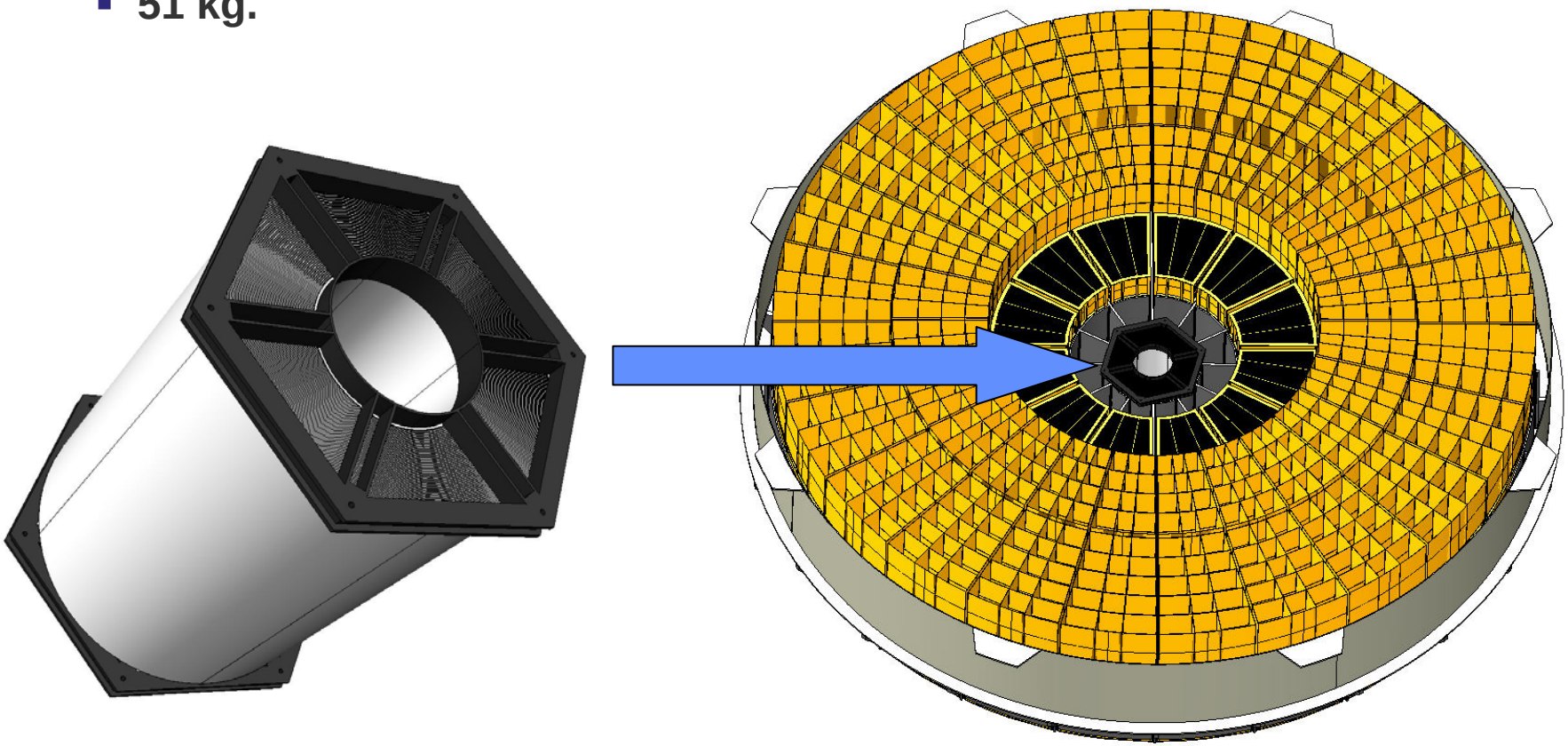
FMA Overview

- Carrier structure supporting 60 SXT modules containing 200-300 bonded-in mirror segments each
  - Overall dimensions: 3.3 m OD x 0.8 m axial depth
- Hard X-ray Mirror Module (HXMM) located at center of structure (not shown)
  - Built using existing technology
- ~1750 kg including HXMM and thermal hardware

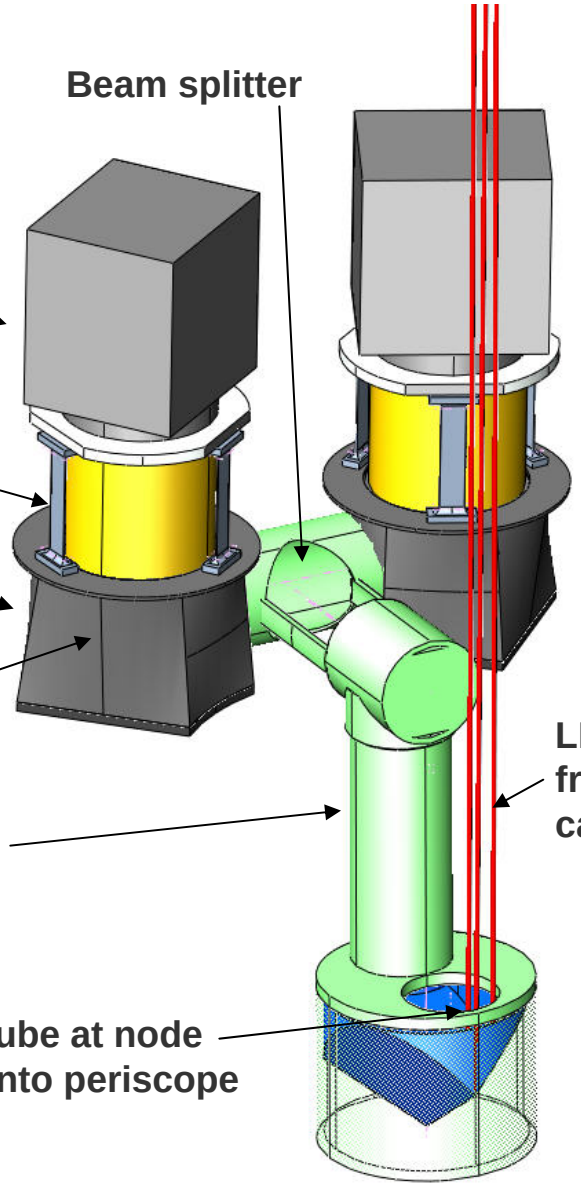


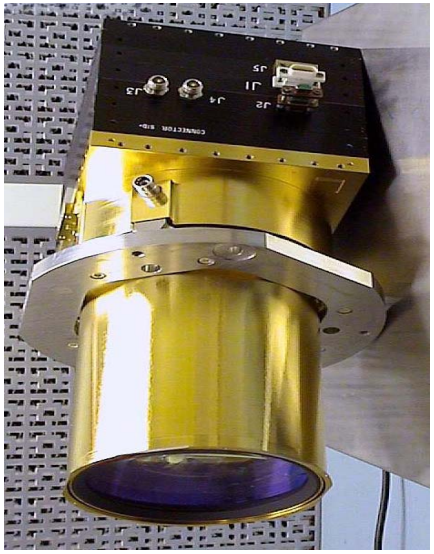
Hard X-ray Mirror Module (HXMM)

- **HXMM will be similar to Suzaku, Astro-H and Nustar designs.**
  - **18cm inner diameter, 42cm outer diameter, 40cm long.**
- **Will be installed into center hole of FMA via flexures.**
- **TADS system fits into the HXMM**
- **51 kg.**



Telescope Alignment and Detection System

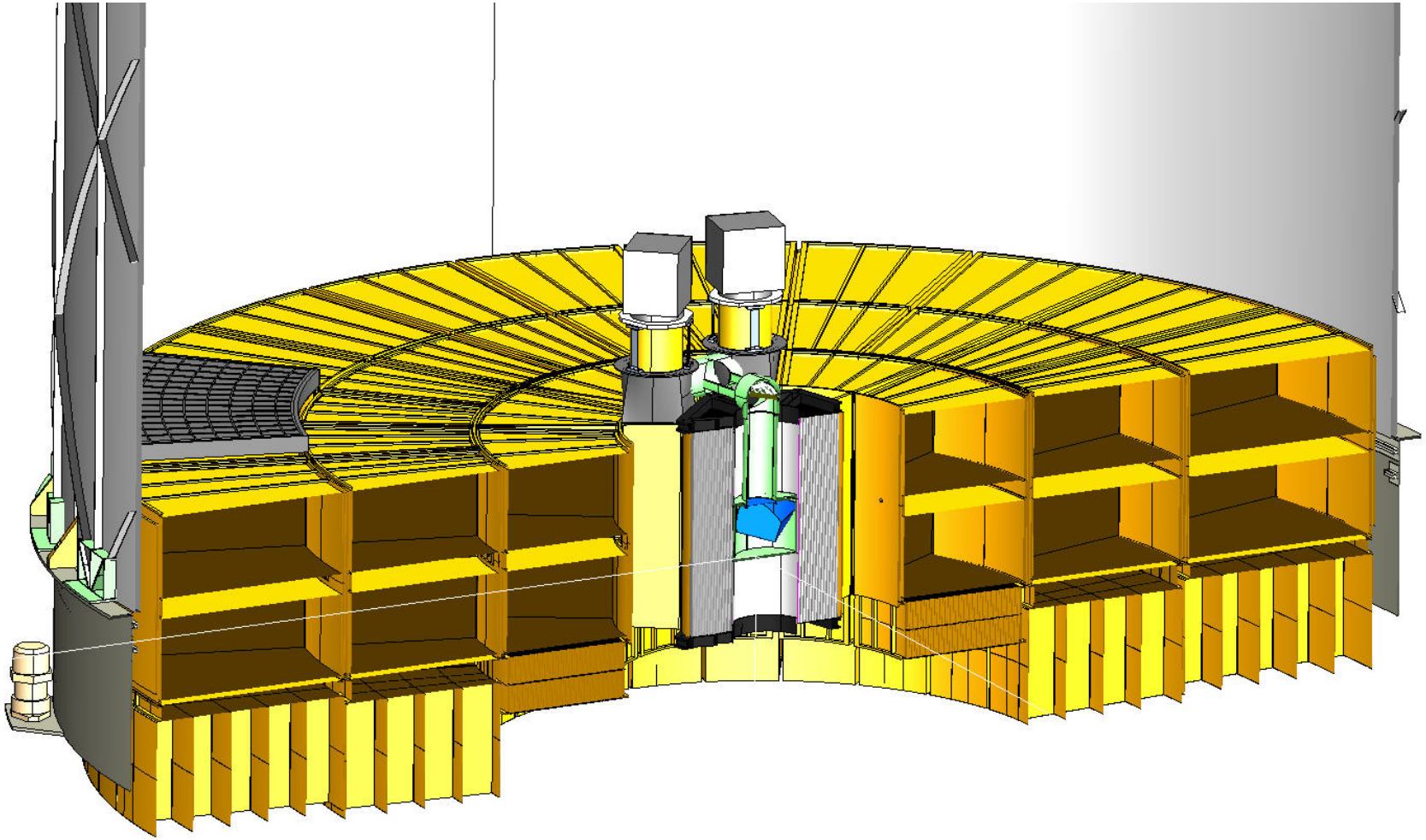




AST-301 Tracker

FID Light (LED light) assembly, 45mm long

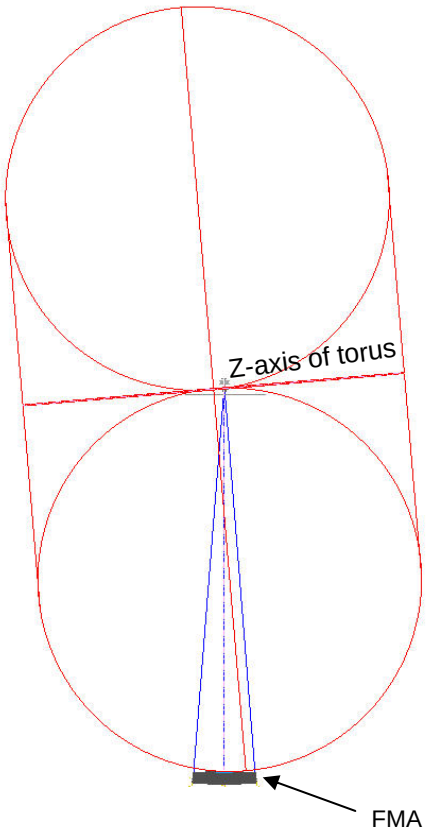
OM and SM Interfaces

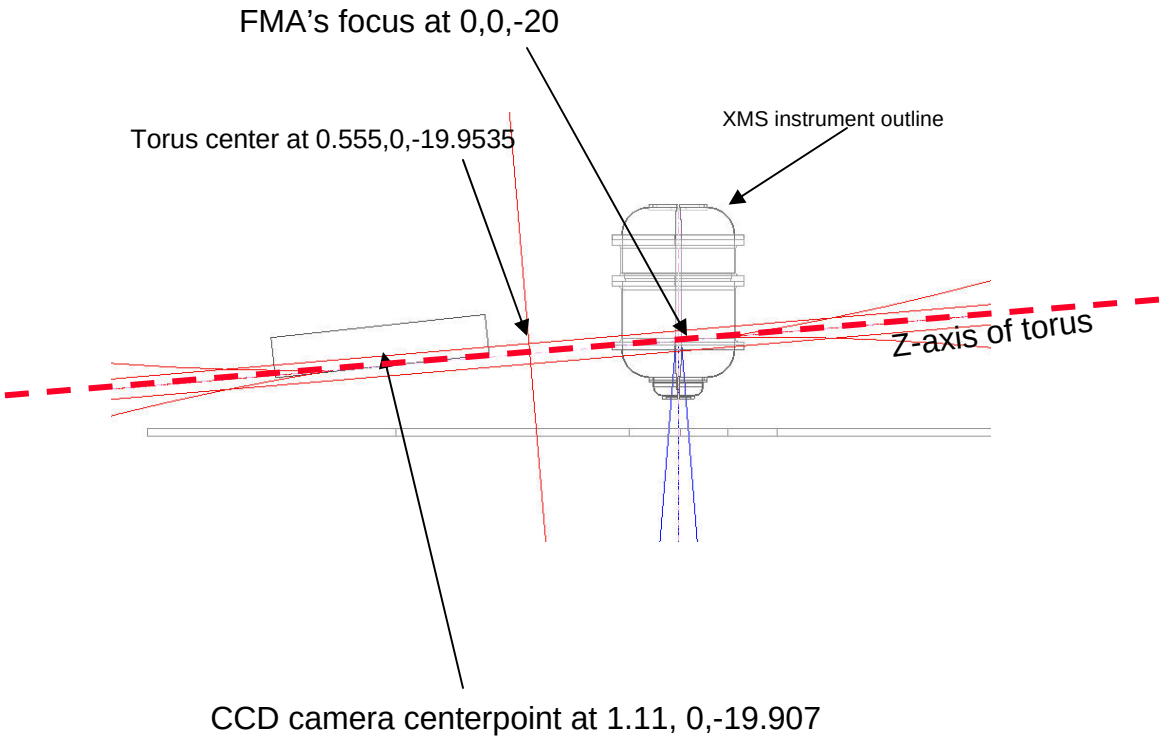


Backup Slides

Orientation of CCD Camera & Gratings: Rowland Torus

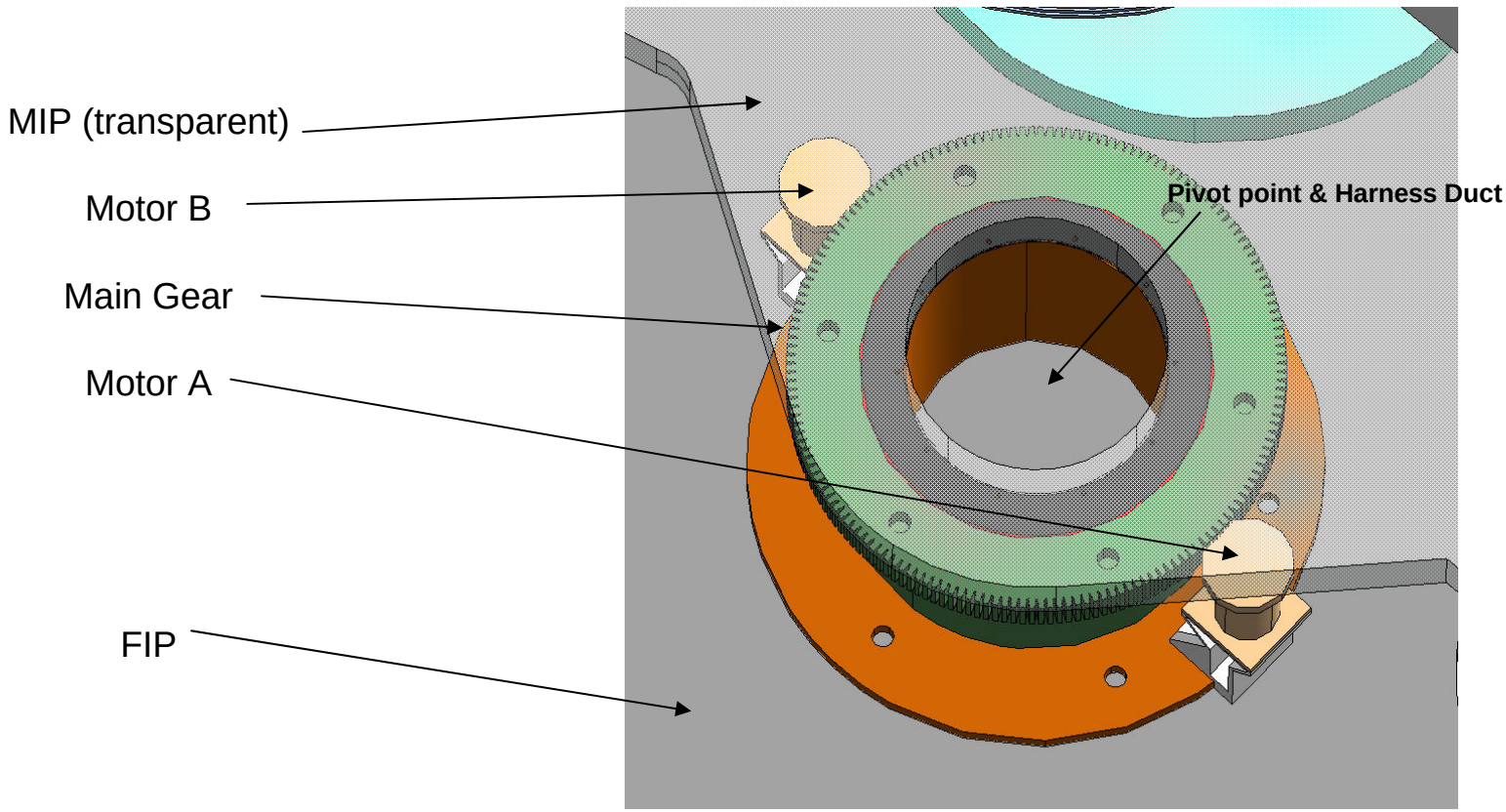
- **The XGS gratings and CCD Camera are placed tangent to the surface of the "Rowland Torus". The distance between is the XGS focal length. This can be different than the "FMA focal length" currently 20m.**
- **For this study, The XGS focal length is 19.705m.**
- **Torus geometry:**
  - **Using standard torus terminology, a = 9.8525m (radius of circle), c = 9.8387m (distance from circle's centerpoint to the axis of rotation "Z")**
  - **Z-axis of torus is a line connecting FMA's focal point to center of CCD Camera.**
- **Center of torus is located halfway between the CCD camera centerpoint and the FMA focal point.**





MIP Rotation Stage's Failsafe Operation

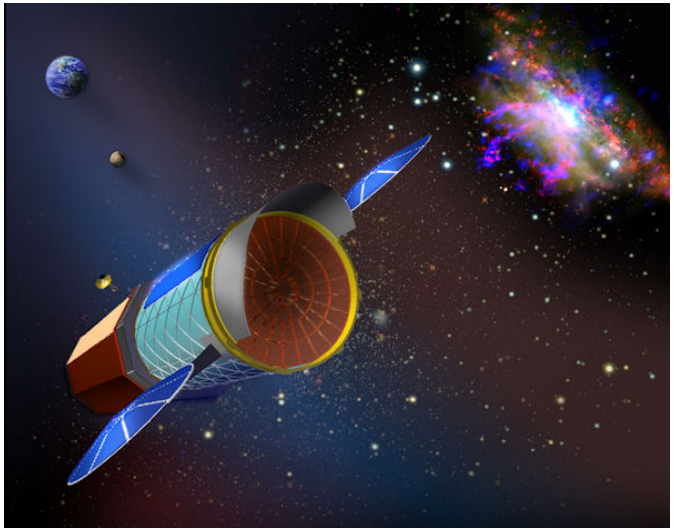
- **During operation, Motor A drives the gear and Motor B is disengaged and freewheels.**
- **If Motor A fails, then a solenoid will be commanded to disengage its clutch while a solenoid on Motor B engages its clutch. Motor B drives the MIP.**



IXO Table Top Review

Integrated Modeling

Dave Robinson / Gabe Karpati
GSFC NASA



Introduction

- To establish the soundness of the observatory configuration, a series of analyses were performed.
- Lockheed volunteered three very senior-level analysts: structural, thermal, and ACS. They worked with us for 6 months and each produced a report which goes into the Observatory Description Document.
- Mechanical and Thermal analyses included:
  - Deployed modes
  - Jitter due to reaction wheels and thruster firing
  - Observatory-level thermal analysis
  - STOP analysis of observatory pointing error due to thermal distortions
  - Bus, MIP and FIP thermal control. Radiator sizing, heat pipe specifications
  - FMA thermal control options

Modeling Applications

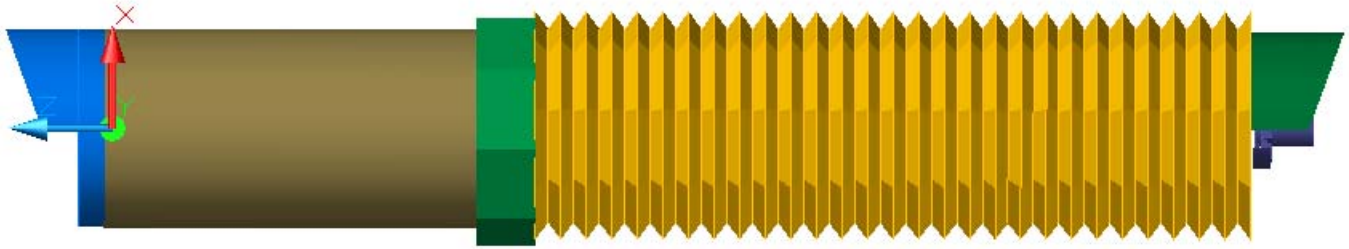
- **Observatory 3-D Thermal Model was used for:**
  - **Observatory thermal design, heater and radiator sizing, component placement, materials selection**
  - **Thermal Analysis in support of Integrated Thermal Distortion Analysis**
  - **FMA Thermal Interface Modeling in support of FMA Temperature Control design**
- **Finite Element Model was used for:**
  - **Modal Analysis**
  - **Jitter Analysis**
- **Integrated Models were used for:**
  - **Integrated Thruster Firing Disturbance Analysis**
  - **Integrated Thermal Distortion Analysis: Thermal + FEM**
  - **Pointing Error Budgeting: Thermal + FEM + GN&C**
  - **Thruster firing effects analyses (deflections and accelerations): FEM + Control System Model (feed forward, etc.)**

Observatory 3-D Thermal Model

- Using Thermal Desktop

IXO Observatory 3-D Thermal Model

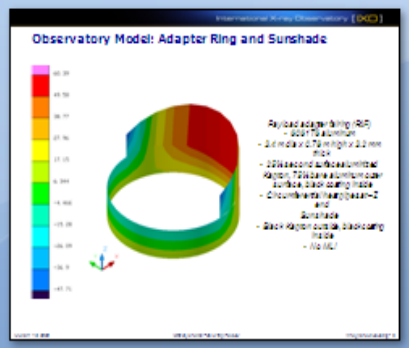
Sunshade *Sunshade*



PAF and FMA *FMS* *SC Bus* *Masts and shroud* *FIP and MIP*

	Nodes	MLI Nodes	Solids	Surfaces
FMA	29	18	1	2
FMS	162	162		2
FIP	40	44	5	12
MIP	68	103	14	3
Masts	531			15
PAF	52			3
SCB	46		6	15
Shroud	525	525		505
Total	1453	852	26	557

Thermal Model Details



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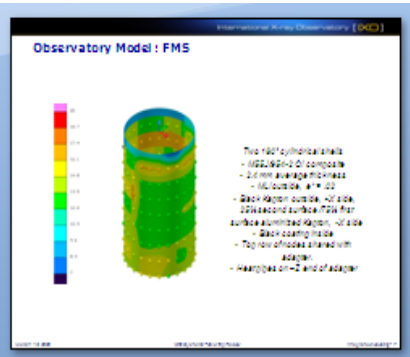

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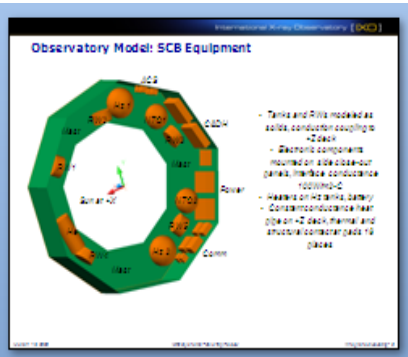

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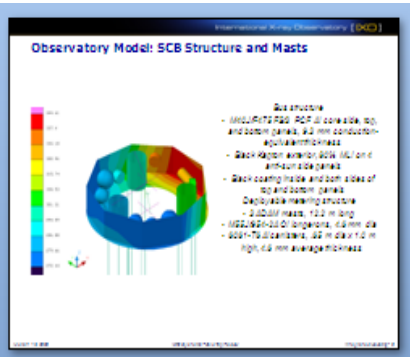

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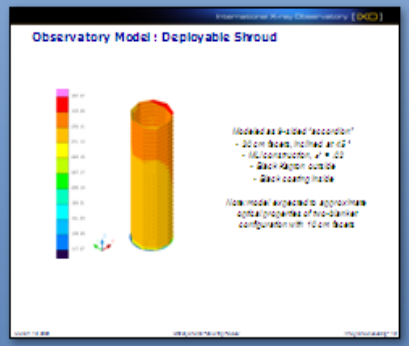

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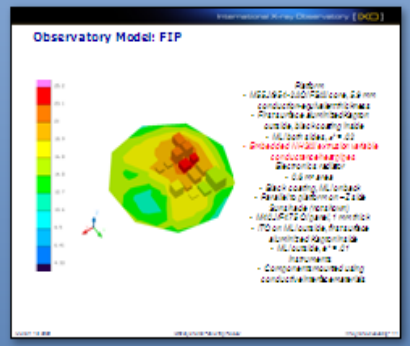

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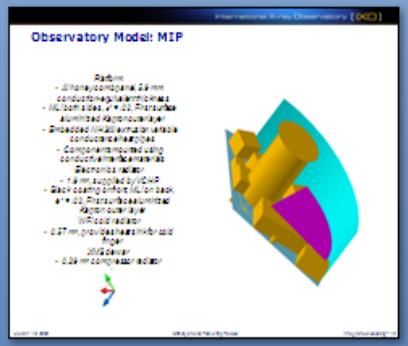

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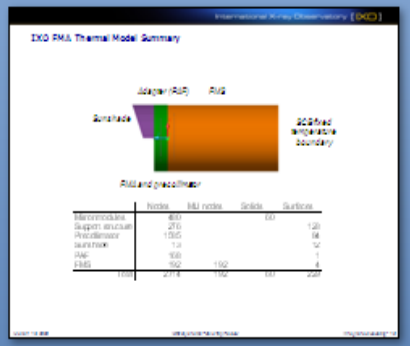

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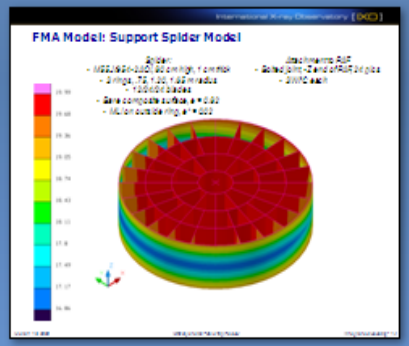

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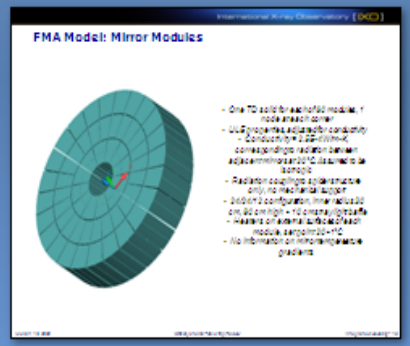

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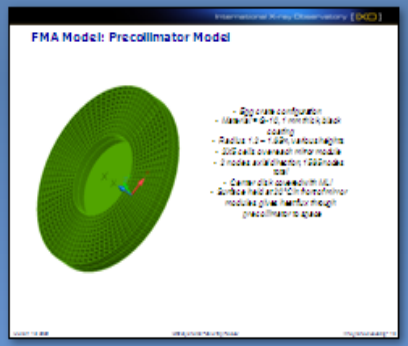

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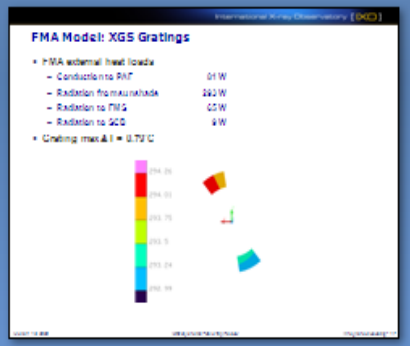
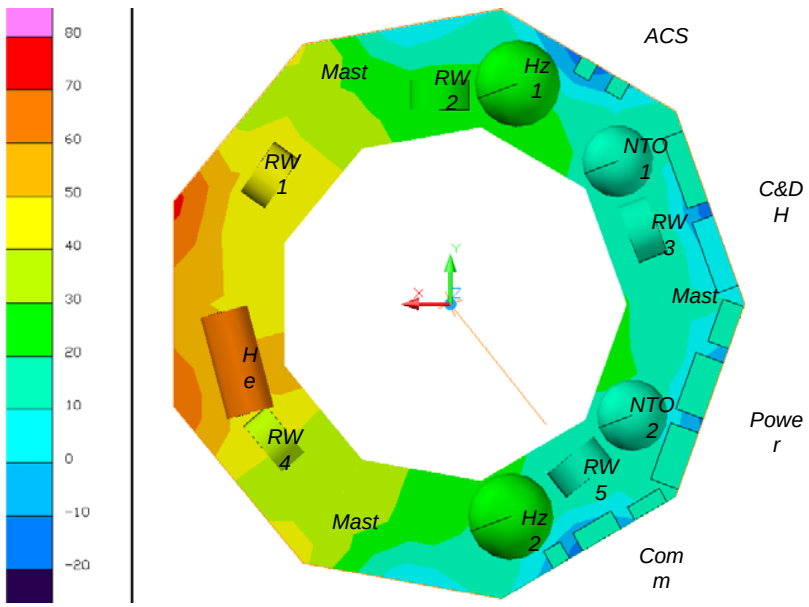


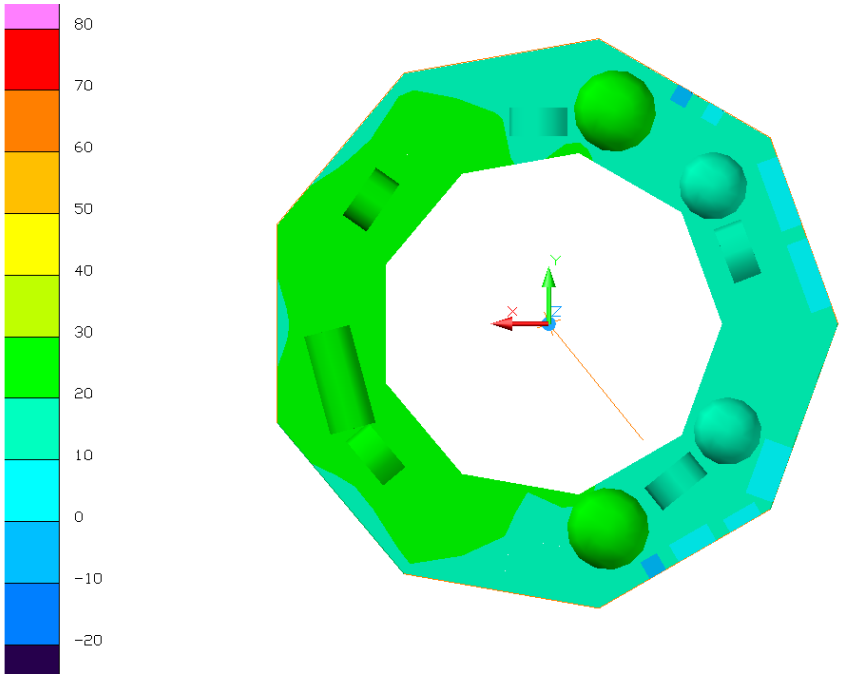
16

Thermal Design Analysis

Thermal Design Optimization - Bus Component Temperatures

w/ Radiation/Conduction Only vs. w/ Circumferential Heat Pipes





Thermal Design - Bus Component Temperatures

Component	Temperature (°C)			Heater Power (W)
	Predicted Downlink	Allowable (1)		
		Min	Max	
DSN S/Ka-Band transmitter 2	18.8	-10	40	
DSN S/Ka-Band transmitter 1	5.1	-10	40	
10 Watt TWTA 1	17.8	-10	40	
10 Watt TWTA 2	0.9	-10	40	
S-band 5 watt power amplifier 1	-1.8	-10	40	
S-band 5 watt power amplifier 2	24.6	-10	40	
C&DH	6.6	-10	40	
C&DH	9.9	-10	40	
Hz Tank 1	28.3	20	30	20
Hz Tank 2	27.4	20	30	20
NTO Tank 1	15.1	0	30	
NTO Tank 2	15.4	0	30	
COPV He Tank PSI 80412-1	26.7	-10	40	
Power system electronics 1	5.1	-10	40	
Power system electronics 2	12.4	-10	40	
50 AH Li-Ion Battery	10.4	25	25	30
Star Tracker Processing Unit 1	13.3	-10	40	
Star Tracker Processing Unit 2	-1.1	-10	40	
Gyro 1	17.7	-10	40	
Gyro 2	1.2	-10	40	
Reaction Wheel 1	29.0	-10	40	
Reaction Wheel 2	19.3	-10	40	
Reaction Wheel 3	15.5	-10	40	
Reaction Wheel 4	25.0	-10	40	
Reaction Wheel 5	15.9	-10	40	

(1) With 10°C margin on operating temperature range

Thermal Design - Payload Component Temperatures

	Component	Status	Predicted	Allowable	
				Min	Max
XMS	Cryocooler Compressor	On	55.2	10	40
	Pre-Amplifier/BiasBox (PBB)	On	4.2	-20	50
	Feedback/Controller Box (FCB) -1	On	4.6	-20	50
	Feedback/Controller Box (FCB) -2	On	5.0	-20	50
	Feedback/Controller Box (FCB) -3	On	5.6	-20	50
	Feedback/Controller Box (FCB) -4	On	5.7	-20	50
	Pulse Processing Electronics (PPE)	On	13.2	-20	50
	ADR Controller (ADRC)	On	4.5	7	27
	Cryocooler Control Electronics (CCE)	On	13.6	10	40
	Filter Wheel Control Electronics (FWC)	On	6.2	10	40
	Power Distribution Unit (PDU) -1	On	8.1	10	40
	Power Distribution Unit (PDU) -2	On	8.8	10	40
WFI	Focal Plane Assembly (FPA)	On	2.5	0	40
	Cold finger	On	-74.0	< -73	
	Hemisphere Pre-Processor-1 (WFI-HPP1)	On	10.7	0	40
	Hemisphere Pre-Processor-2 (WFI-HPP2)	On	11.0	0	40
	Brain/Frame Builder-1&2	On	4.1	0	40
	Power Conditioner-1 (WFI-PCU1)	On	10.5	0	40
	Power Conditioner-2 (WFI-PCU2)	Off		0	40

On/Off status for Mode 2 plus full XMS warm-up

Thermal Design - Payload Component Temperatures (cont.)

	Component	Status	Predicted	Allowable	
				Min	Max
HXI	Sensor Head (HXI-S)	On	2.5	-22	-18
	Analog Electronic Unit (HXI EA)	On	3.1	0	40
	Digital Electronics (HXI DE)	On	7.3	0	40
	PSU (HXI PSU)	On	8.4	0	40
XGS	Grating Array-1	On	20.4	19	21
	Grating Array-2	On	19.9	19	21
	CCD Camera	On	-100.2	-90	-70
	Power Supply & Mech Controller (DEMP)	On		-30	
	Digital Processing Electronics (DPA)	On	6.3	-30	10
XPOL	Focal Plane Assembly (XPOL-FPA)	Off	1.4	-15	45
	Backend Electronics (XPOL-BBE)	Off	2.1	-15	60
	Control Electronics (XPOL-CE)	Off	6.1	-15	60
HTRS	Focal Plane Assembly (HTRS-DEU)	Off	2.3	-40	35
	Central Electronic Unit (HTRS-CEU)	Off	2.6	-40	35

On/Off status for Mode 2 plus full XMS warm-up

Thermal Design - Heat Pipe Mass Estimate

		Ea	No req'd	Ext
Adapter	CCHP	5.6	3	16.7
SCB	CCHP	8.3	2	16.5
FIP	VCHP	3.4	2	6.9
MIP	VCHP	3.1	2	6.3
Subtotal		20.4		46.4
Contingency				30%
Total				60.3

Notes: Number required includes redundancy
SCB heat pipe weight includes mounting pads
Heat pipes are flight proven NH3/Al extrusion design, 350 W-m capacity

Thermal Design - MLI Mass Estimate

	Area (m2)	Mass (kg)
Adapter	8.3	2.6
FMS	67.9	21.5
SCB	5.4	1.7
FIP panel	18.2	5.7
FIP elex radiator	0.7	0.2
MIP panel	3.8	1.2
MIP elex radiator	1.8	0.6
WFI cold radiator	0.5	0.1
Subtotal		33.7
Contingency		30%
Total		43.8

Notes: 20 layer blanket, .25 mil embossed Mylar inner layers
2 mil Kapton outer layers
Does not include deployable shroud

Thermal Design - IM Radiator Mass

- *Estimate based on Mode 2 + full XMS average power.*
- *VCHP will accommodate lower power modes*
- *Estimate includes facesheets, core, adhesives, coatings, MLI on back, plus 25% for structure*
- *Temperatures and heat loads from observatory thermal model*

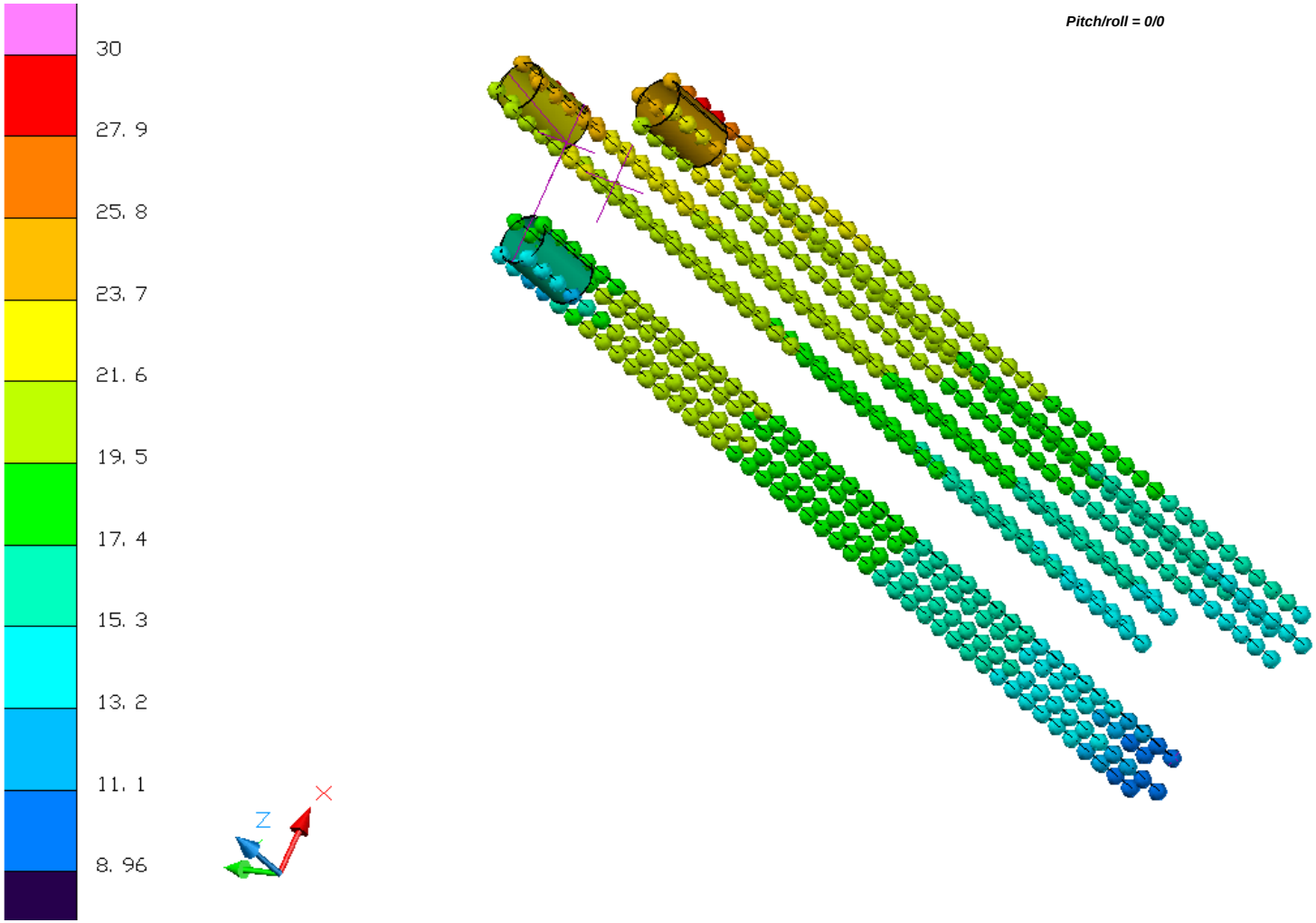
	Area (m^2)	Mass (kg)
MIP electronics	0.88	5.1
WFI cold finger	0.38	2.6
XMS compressor	0.71	4.2
FIP electronics	1.25	7.4
XGS camera	0.30	1.9
Total		21.2

Thermal Distortion Analysis
in support of Integrated Thermal Distortion Analysis

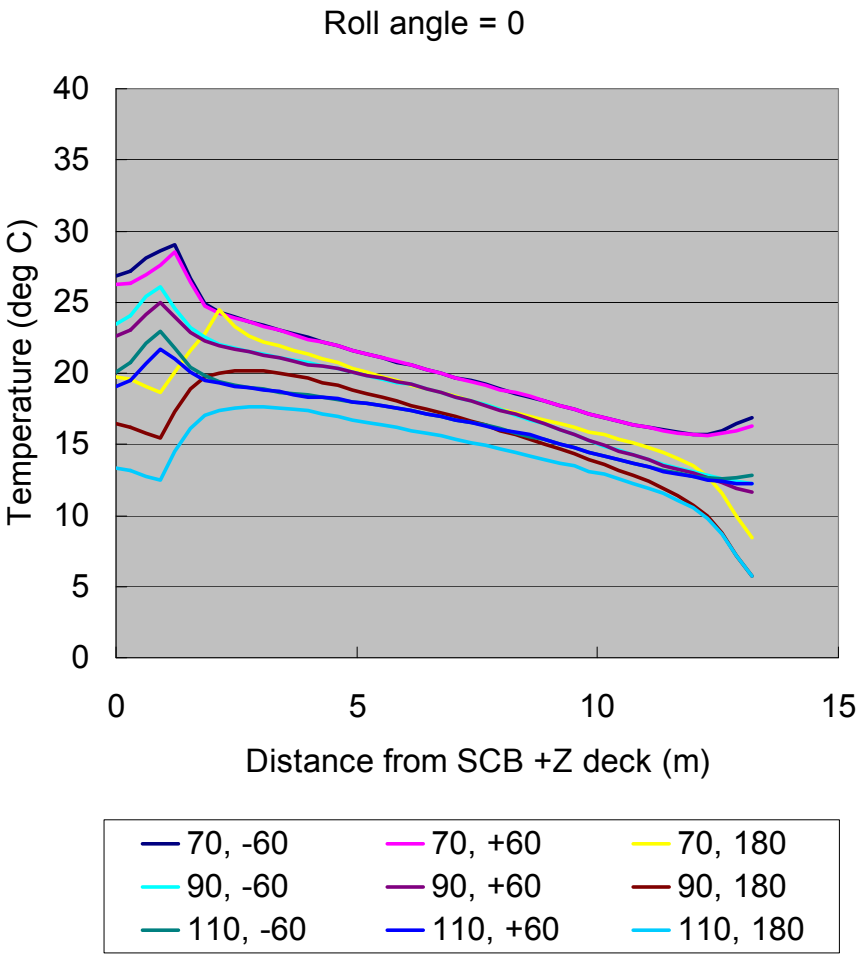
Thermal Distortion Analysis Cases

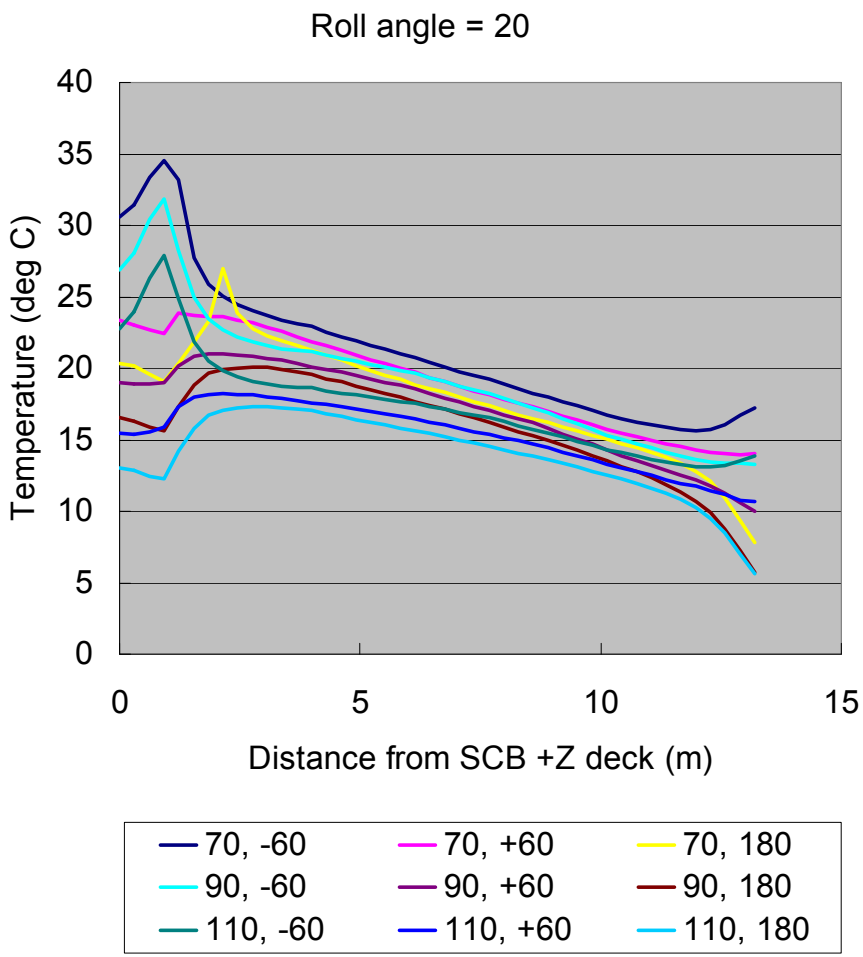
- 6 cases, steady state
  - Pitch = 90° ± 20°, Roll = 0
  - Pitch = 90° ± 20°, Roll = 20°
- Assume symmetry for -20° roll angle
- Numerical results provided for FMS, adapter, FMA structure, SC bus, and FIP.
  - Nodal temperatures specified as function of position

Thermal Distortion Analysis - Mast Temperatures



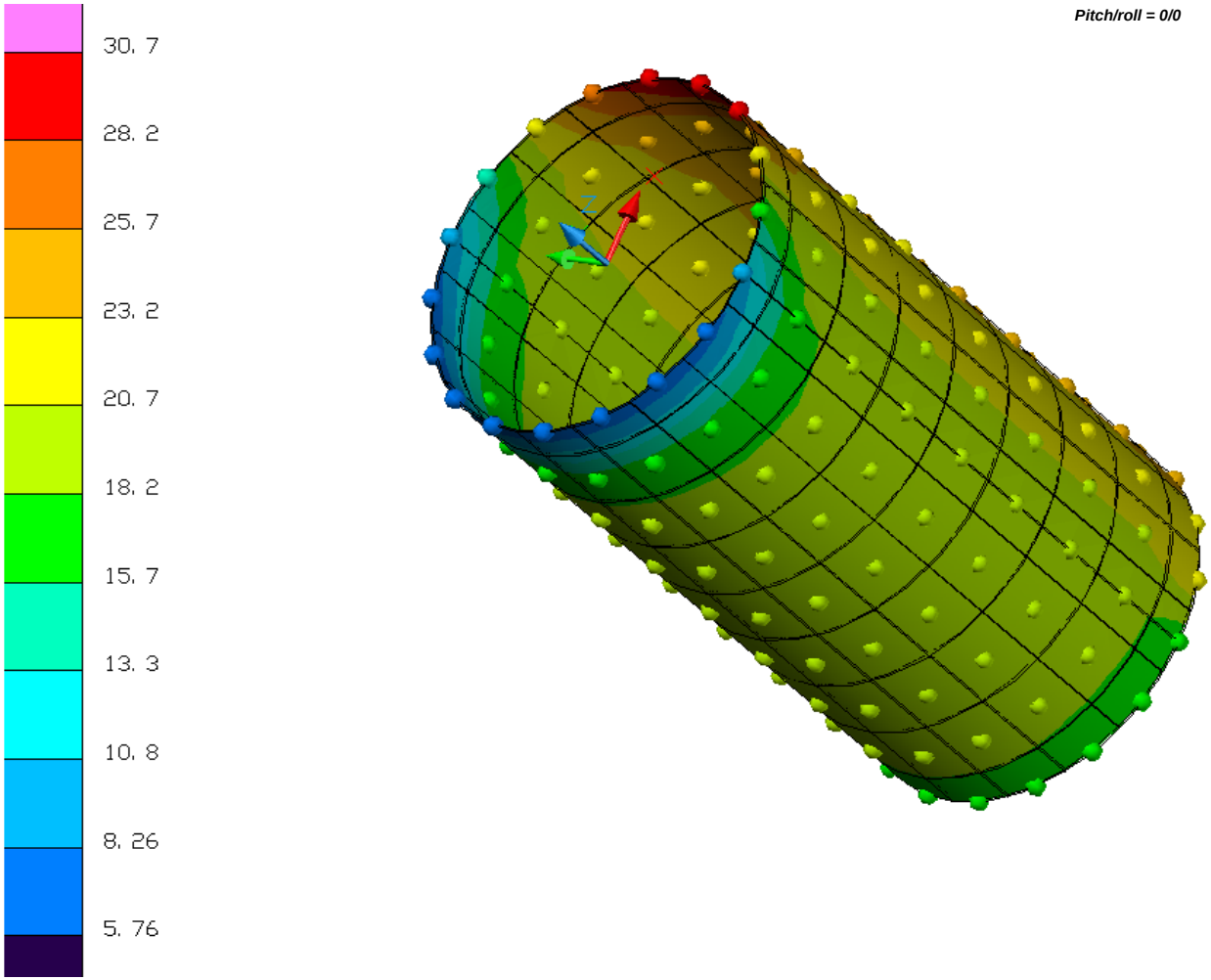
Thermal Distortion Analysis - Mast Temperatures, Numerical Results



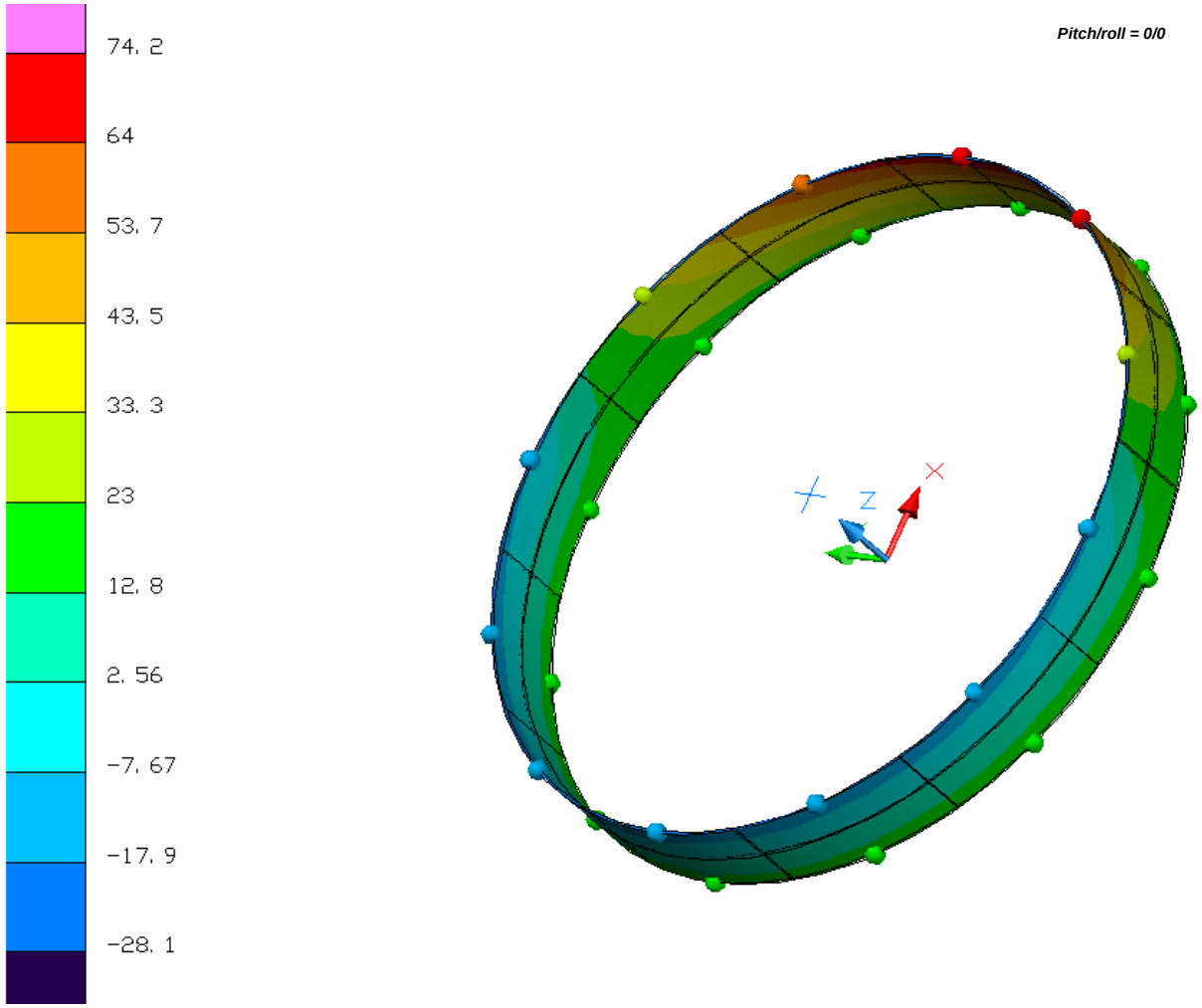


<u>Legend</u>: *First number is pitch angle, measured from telescope axis*
Second number is mast angular position, measured from +X axis

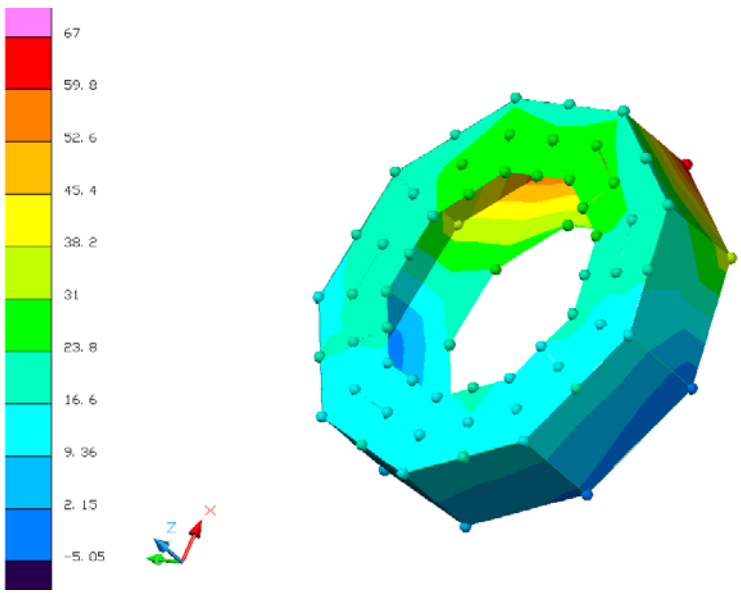
Thermal Distortion Analysis - FMS Temperatures

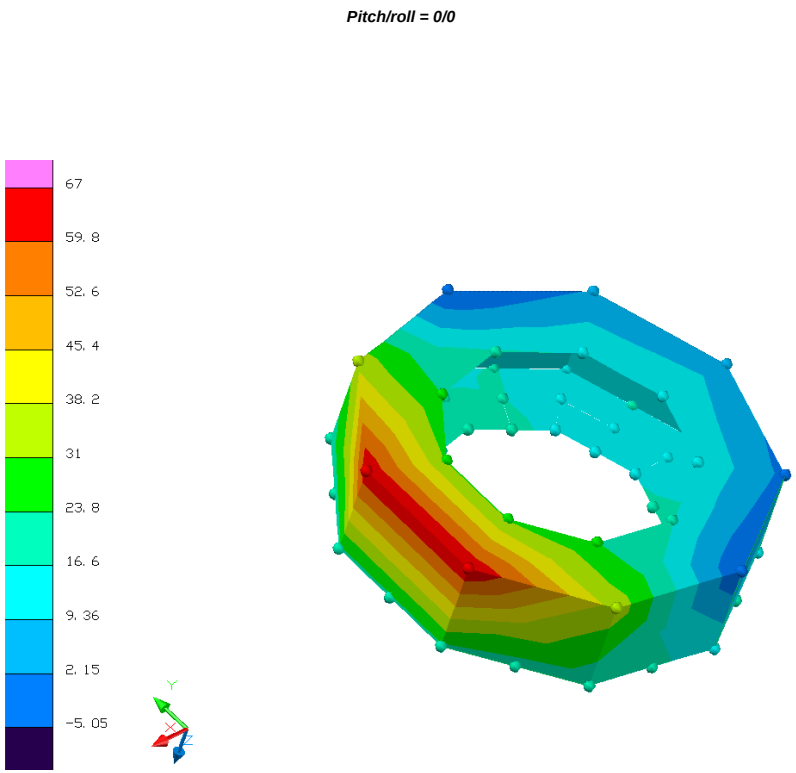


Thermal Distortion Analysis - PAF Temperatures

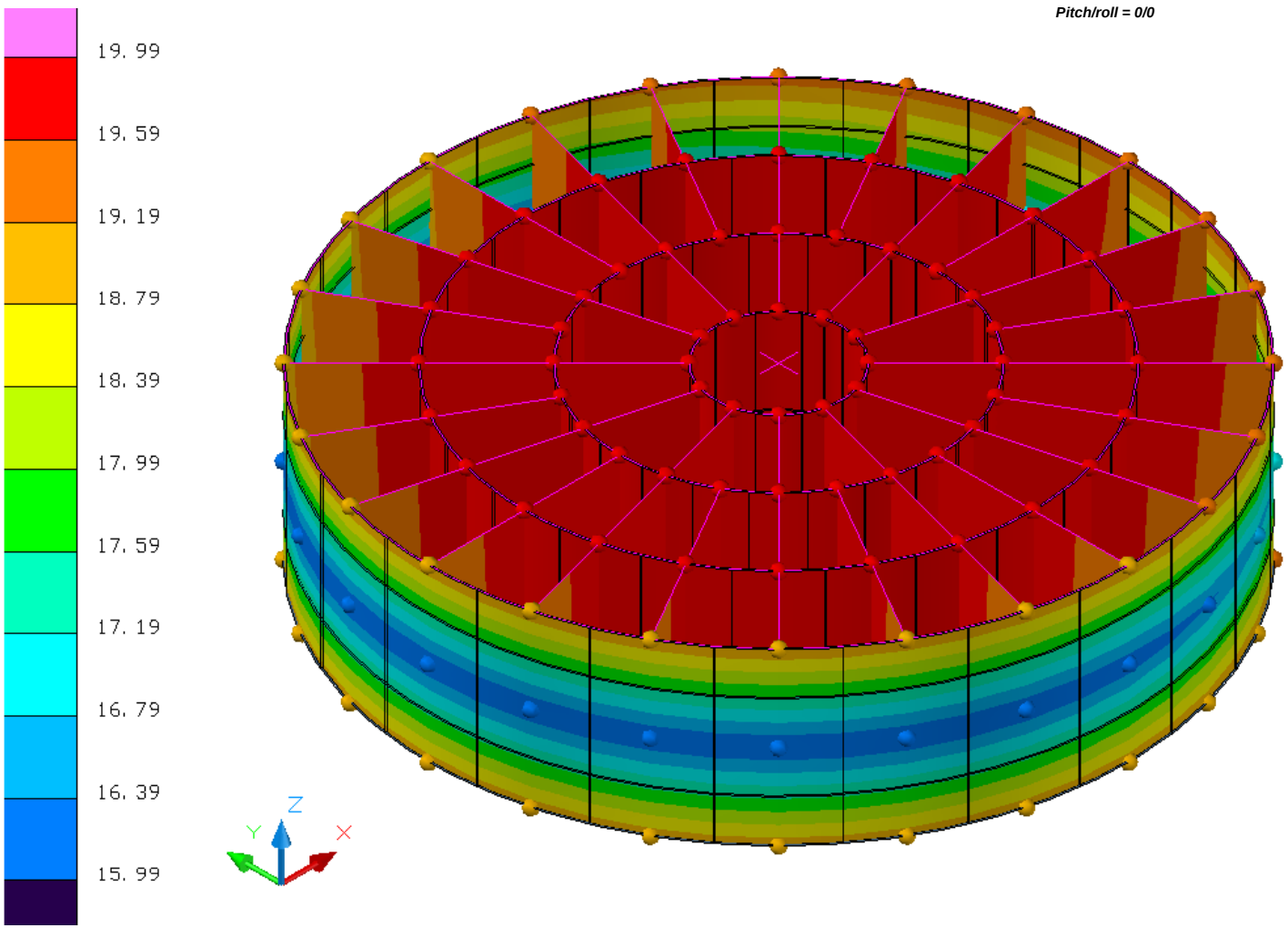


Thermal Distortion Analysis - Bus Structure Temperatures, +Z and –Z side

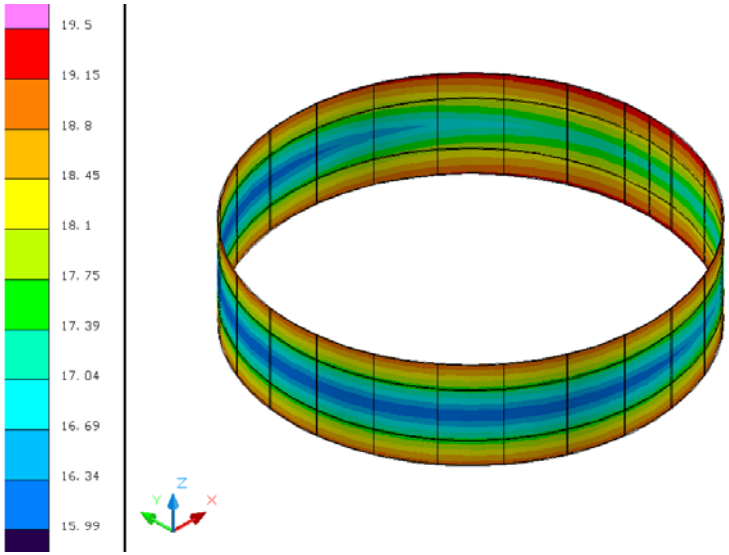


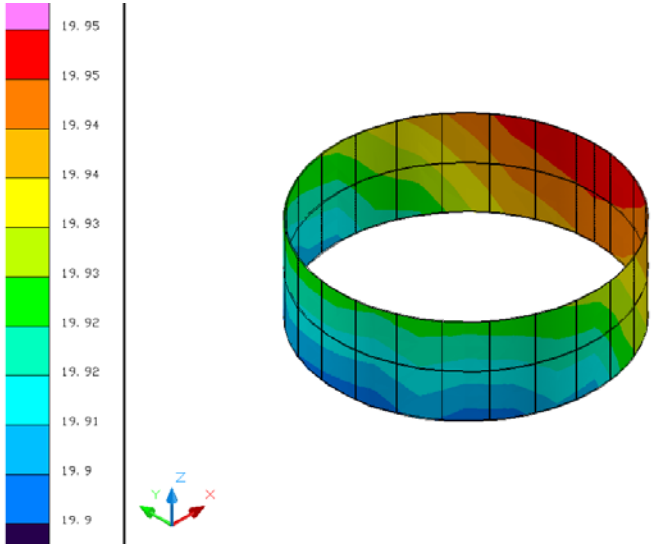


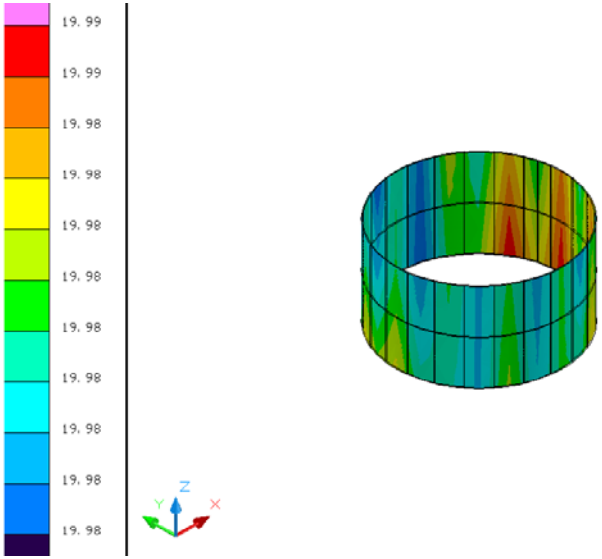
Thermal Distortion Analysis - FMA Temperatures

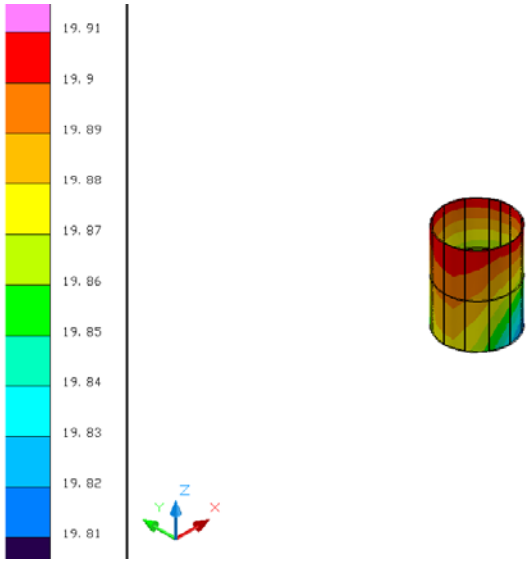


Thermal Distortion Analysis – FMA Ring Temperatures



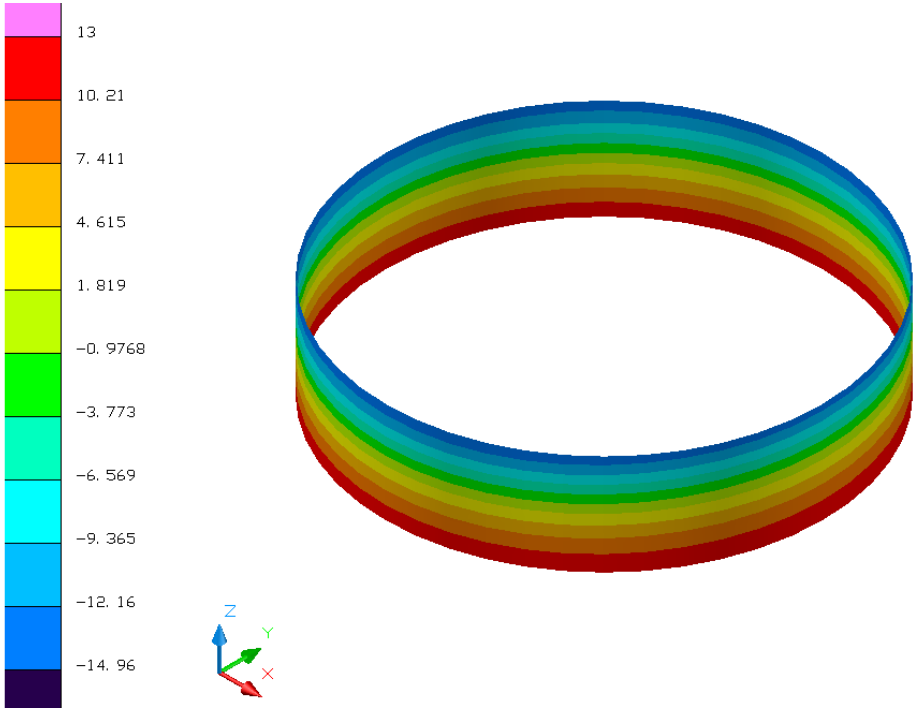






FMA Thermal Interface Analysis

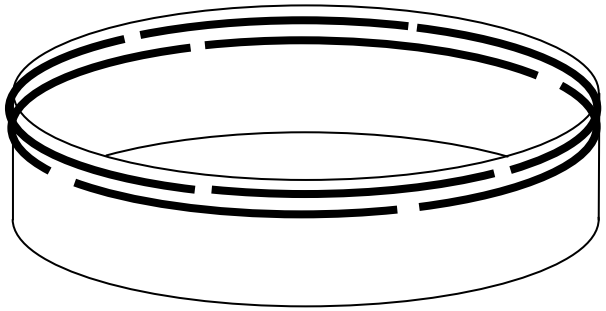
FMA Thermal Interface Modeling - Payload Adapter Temperature Distribution



- *Heat pipes at both ends*
- *Conductive silver composite coating, MLI outside*
- *Assume 3.2 mm thick*
- *No heaters on FMS*

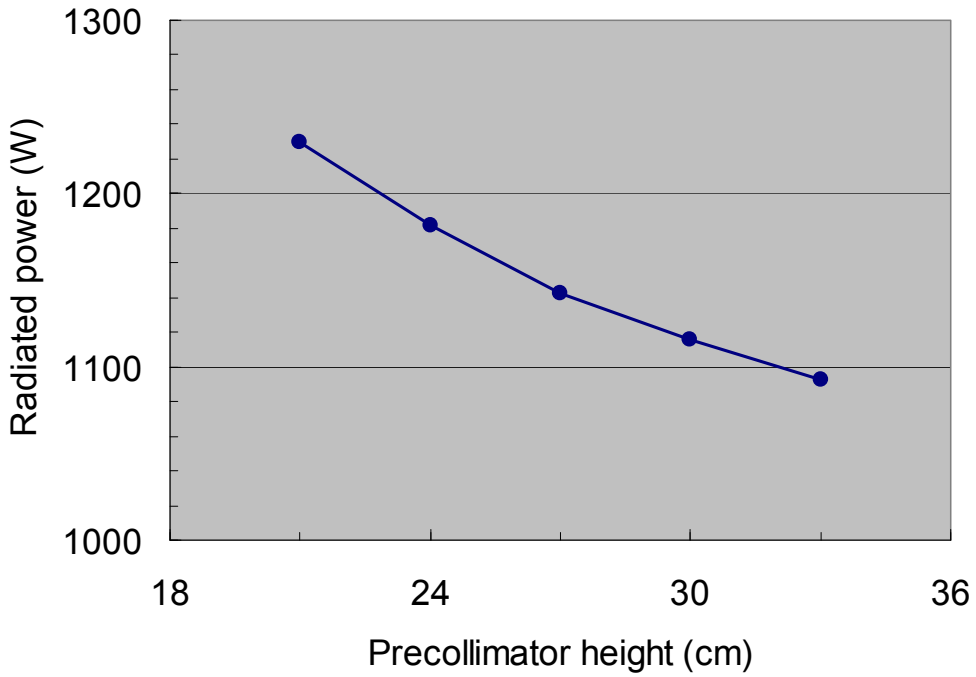
Observatory Model: Adapter Heat Pipe Configuration

- *Typical heat pipe extrusion length is 10 ft. Two rings with overlapping CCHPs provide redundancy, thermal continuity. HP size is ~0.5 in. square. Can be mounted inside. Expect to use high conductivity adhesive, e.g., McGann Nusil CV2942*
- *Early calculations assume pipes are at –Z end. To avoid gradients, can mount second set of pipes at other end of adapter.*



FMA Thermal Interface Modeling - Heat Loss Through Precollimator, Effect of Precollimator Thickness

- *Black body surface behind precollimator, 20°C, mirror side inactive*
- *Exterior coatings:*
  - *Black Kapton on sunshade*
  - *25% second surface aluminized Kapton/75% bare aluminum on PAF and back of FMS*
  - *1 mil thick second surface aluminized Kapton on sun side of FMS*

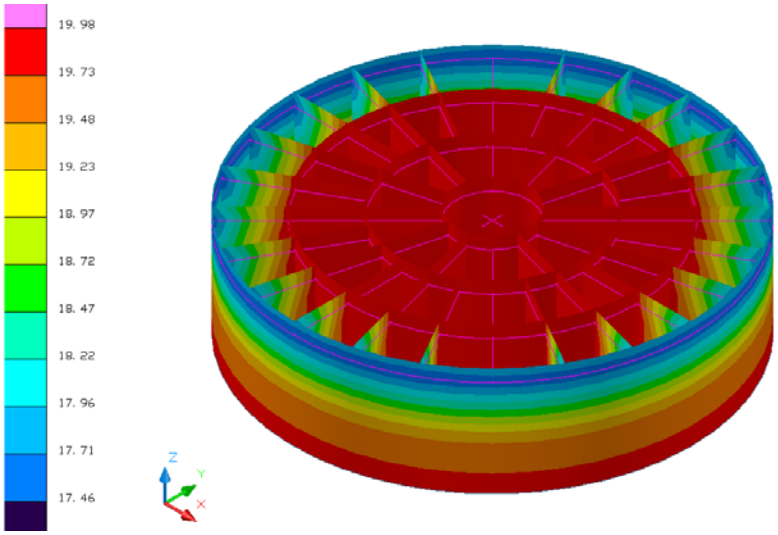


FMA Thermal Interface Modeling - Heat Loss Through Precollimator, Effect of Observatory Attitude

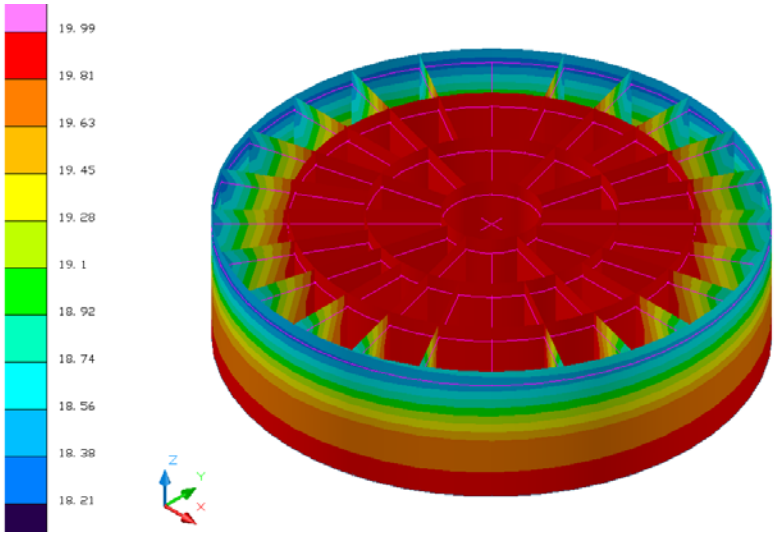
- *Black body surface behind precollimator, 20°C, mirror side inactive*
- *Exterior coatings:*
  - *Black Kapton on sunshade*
  - *25% second surface aluminized Kapton/75% bare aluminum on PAF and back of FMS*
  - *1 mil thick second surface aluminized Kapton on sun side of FMS*

Attitude		Heater power (W)		
Pitch	Roll	+Z face	modules	total
70	0	912	215	1127
90	0	901	187	1088
110	0	913	221	1133
70	20	902	202	1104
90	20	907	190	1097
110	20	921	227	1148
Precollimator height = 27 cm				

FMA Thermal Interface Modeling - FMA Structure Temperatures with Ag Composite Coating

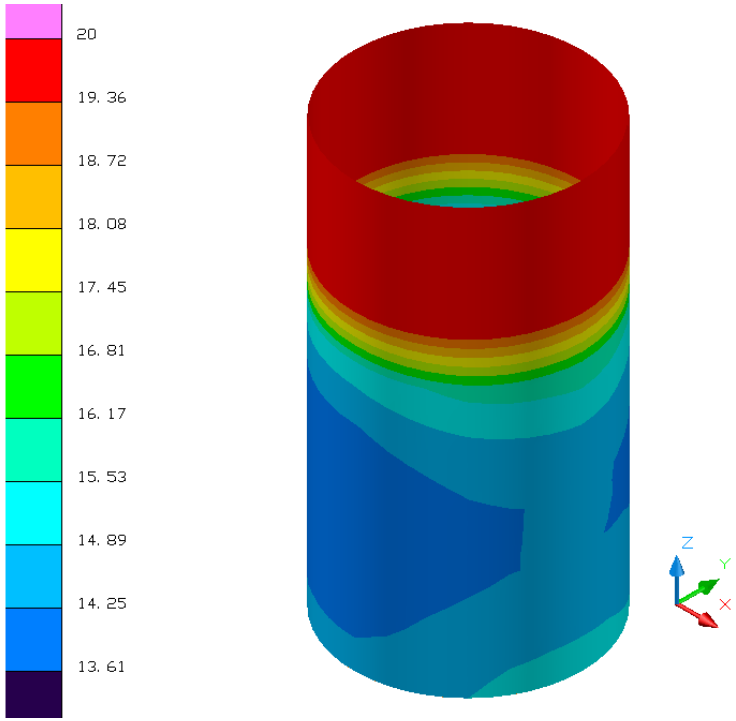


BOL, 17.46 – 19.98°C

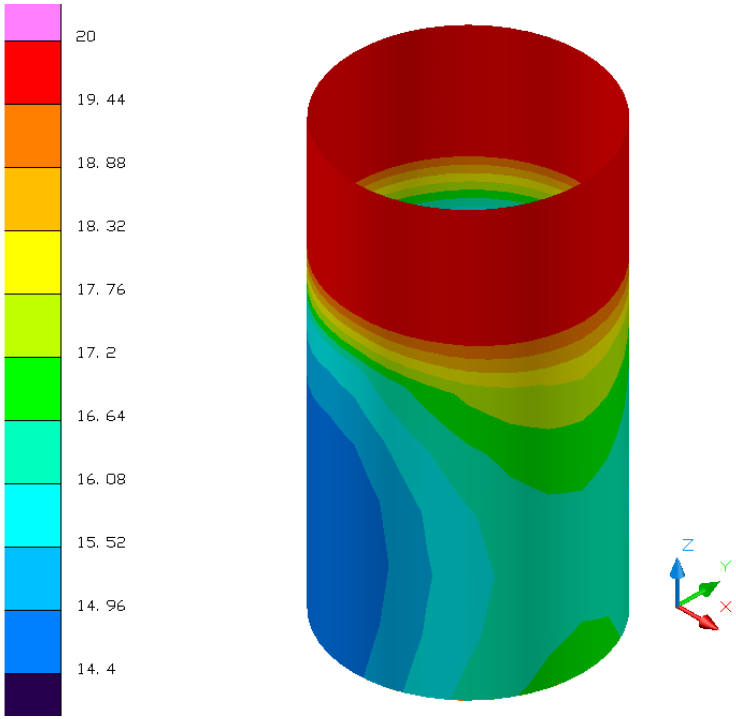


EOL, 18.21 – 19.99°C

FMA Thermal Interface Modeling - FMS Temperatures with Ag Composite Coating

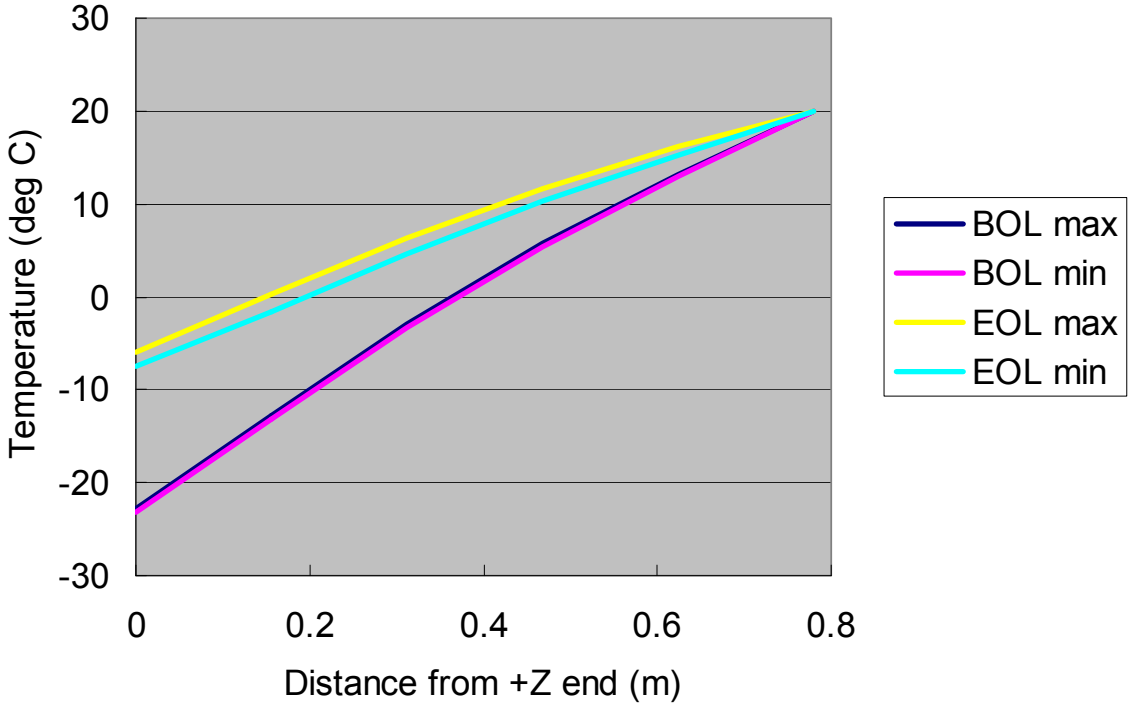


BOL, 13.61 – 20.00°C



EOL, 14.40 – 20.00°C

FMA Thermal Interface Modeling - Payload Adapter Temperatures with Ag Composite Coating



- *Heat pipes at both ends*
- *Conductive silver composite coating, MLI outside*
- *Assume 3.2 mm thick aluminum*

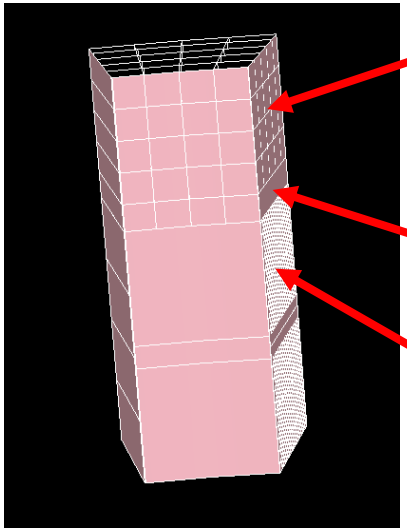
FMA Thermal Interface Modeling - Heat Loss with Ag Composite Coating

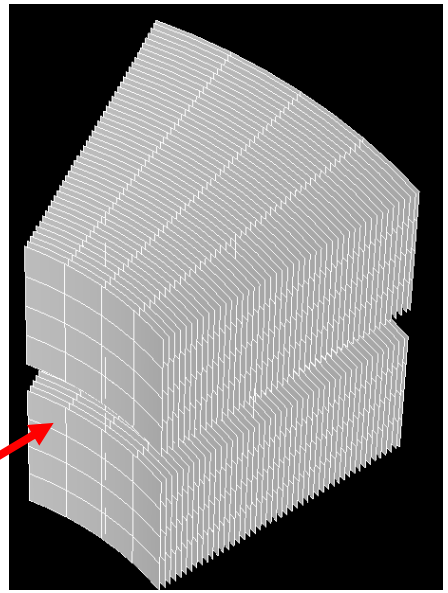
	BOL	EOL
Through precollimator	1072	1029
Mirror modules	164	116
FMS heaters	237	176
Total	1473	1321

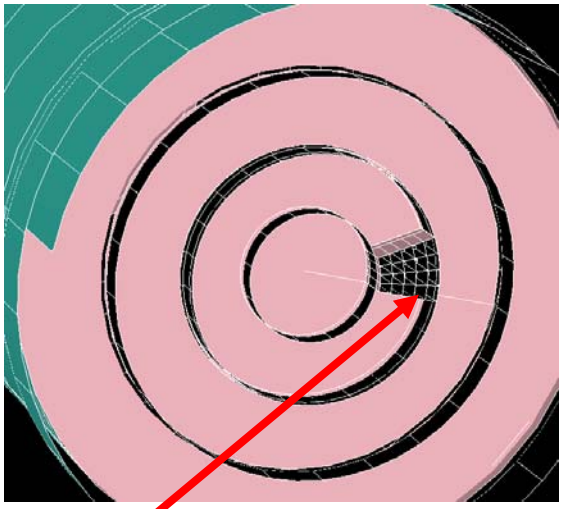
- *Conductive silver composite coating on exterior surfaces of FMS, adapter, and sunshade, a/e = .08/.6 BOL, .25/.58 EOL. Black inside, e = .8*
- *MLI outside FMS and adapter, e* = .02*
- *Mirror modules black, radiation coupling to frame components. Heaters on module surfaces, 20 ± 1°C setpoint*
- *FMS heaters on 1.59 m length at +Z end, 20 ± 1°C setpoint*
- *Heat loss through precollimator calculated assuming constant temperature 20°C surface behind precollimator*

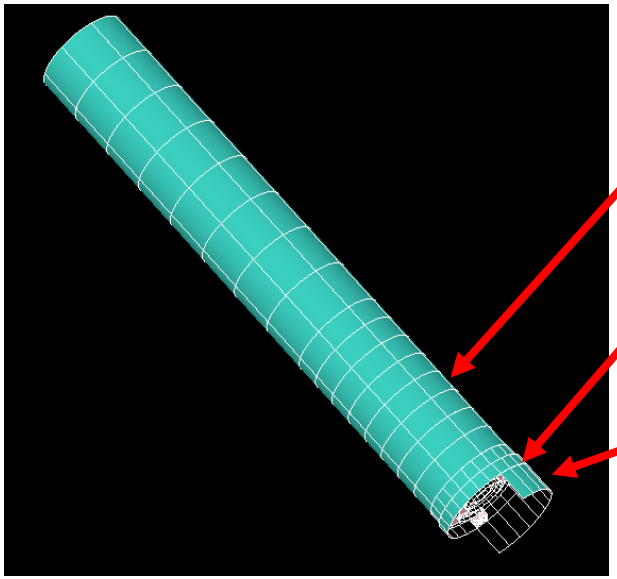
FMA Thermal Modeling

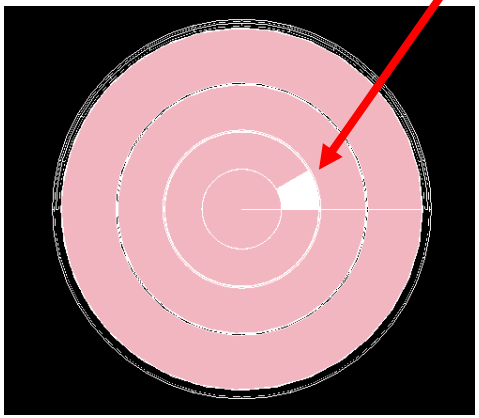
SXT Thermal Modeling / Assumptions

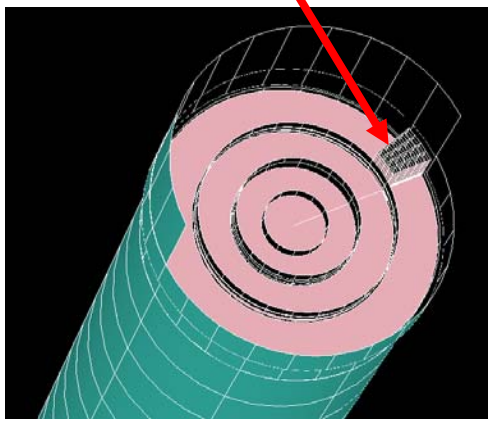












SXT Thermal Modeling / Assumptions

- Each mirror module has its own heater control and is thermally independent of other modules
- Each mirror segment has 16 nodes on each side
- Only one module is included in thermal model at a time for temperature predictions due to very large number of surfaces of all 60 modules and size of radiation couplings
  - Nearly 5 million radiation couplings for one module and file is larger than 300K KB
  - A different model for inner, middle or outer modules
  - Total heater power is calculated for all 60 modules based on number of modules and heater power for each module
- Mirror is thin glass and coating is iridium
  - Very low thermal conductivity (~1 $Wm^{-1}K^{-1}$)
  - Emittance is 0.05 and specular
- Backside of mirror is glass with no coating (high emittance) due to stray light
- Conduction path from mirror segments to module enclosure is very low

SXT Thermal Modeling / Assumptions

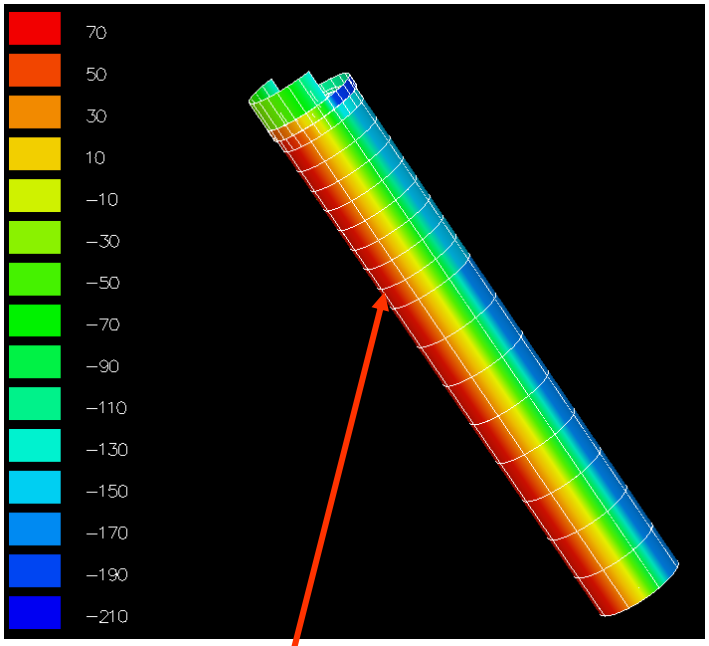
- Pre-collimator has very low thermal conductivity
  - Fiberglass, G-10, etc.
- Interior of metering structure has a high emittance to enhance heat radiation from sun side to anti-sun side
- Anti-sun side of sunshade is black Kapton
- Heater controllers have ±0.1°C tolerances or better

	BOL		EOL (5 Years)	
Coating	Absorptance	Emittance	Absorptance	Emittance
Conductive Silver Composite	0.08	0.60	0.25	0.58
Germanium Kapton	0.45	0.78	0.56	0.76

SXT Thermal Predictions

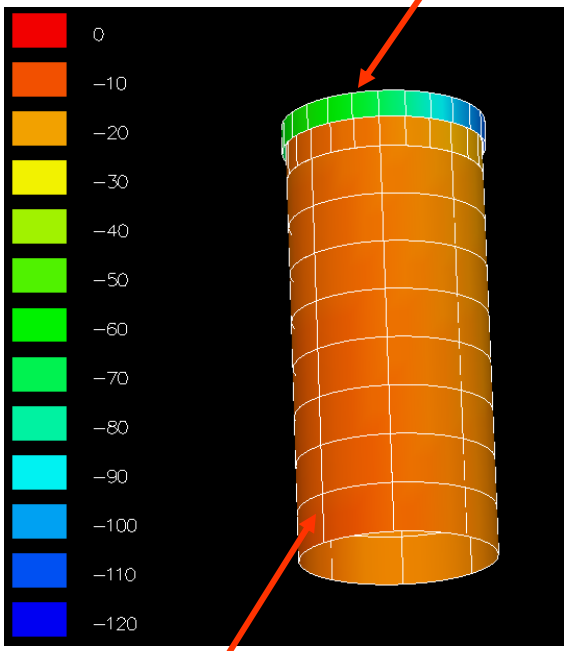
Worst Hot Case, No Active Heater Control, Sufficiently Cold Biased.

Temperature in °C

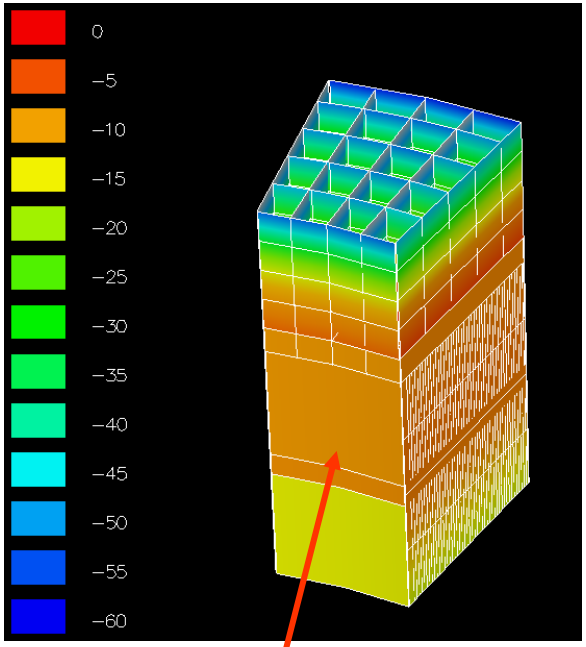


MLI

Adapter



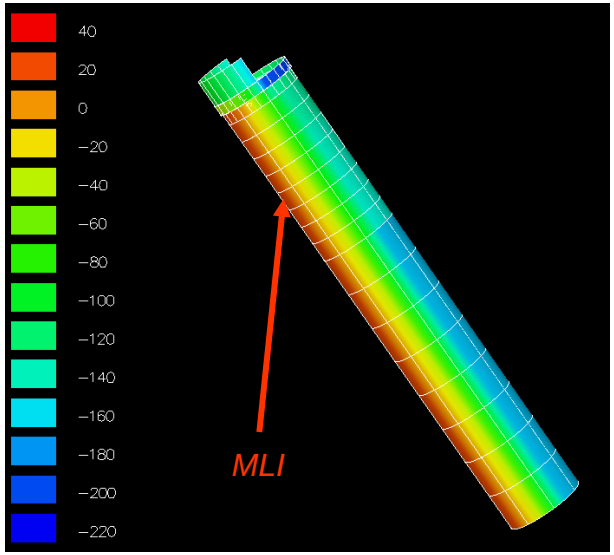
Metering Structure (M55J)

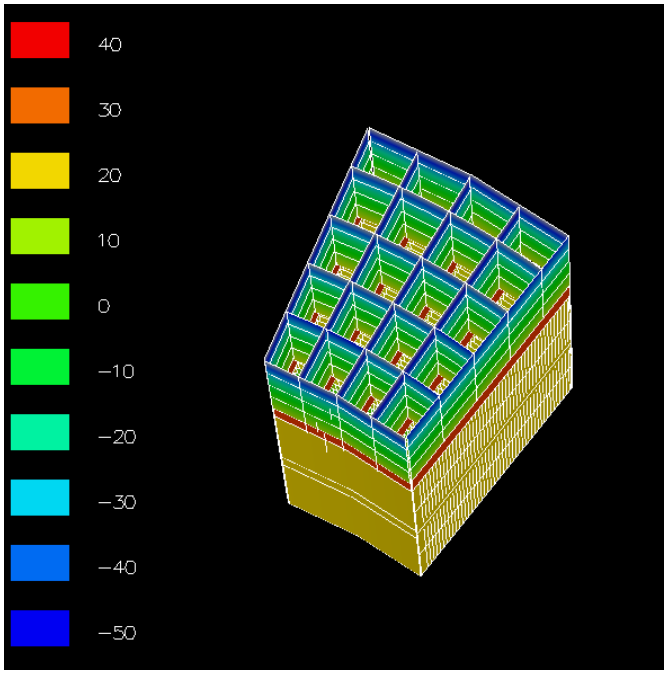


Outer Mirror Module

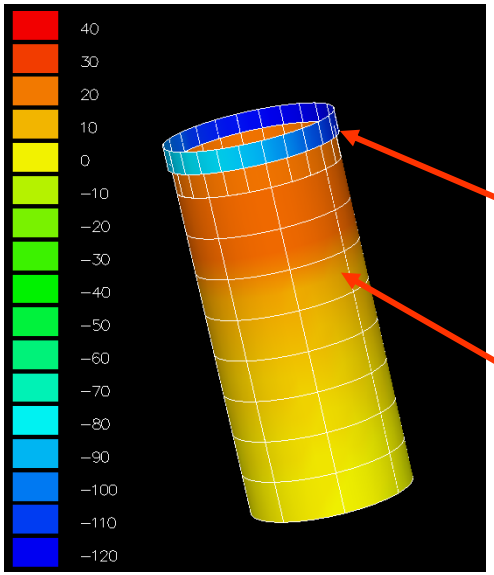
SXT Thermal Predictions

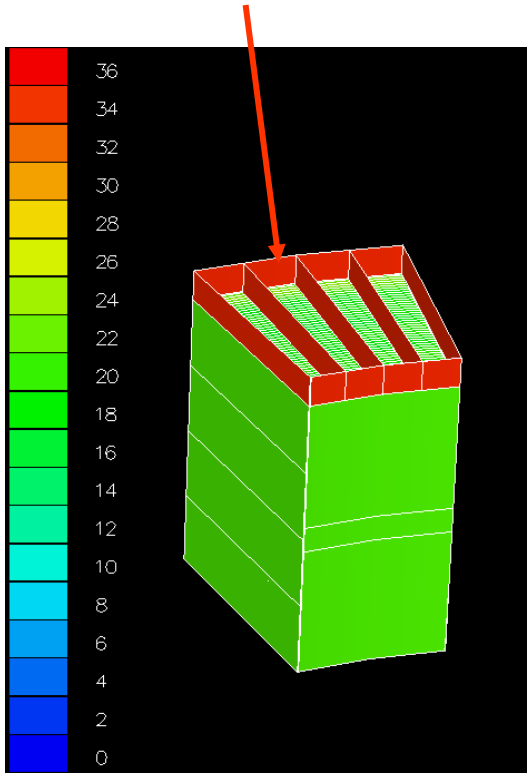
Worst Cold Case, Active Heater Control
Temperature in °C





Outer Module





SXT Heater Power Predictions

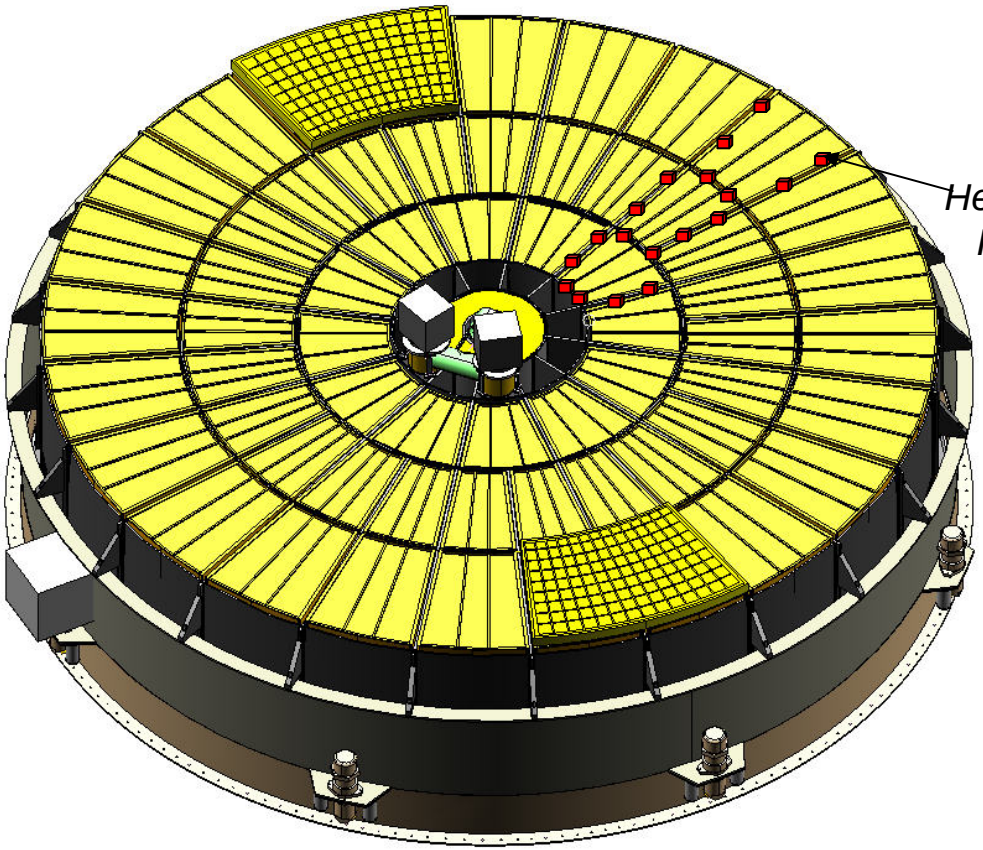
	Heater Power (W)*
Outer Modules	650
Middle Modules	360
Inner Modules	100**
Metering Structure	420
Total	1530

**BOL worst cold case.*
***A thin aluminized Kapton layer on top of stray light baffle. Aluminum side facing optics.*

Approach to Minimize SXT Heater Harness Mass

Distributed Heater Controller Approach:
Use multi-channel and small heater controllers, like those flown on Swift BAT.*
Mount module heater controllers to structure members adjacent to each module.
Mount metering structure heater controllers to metering structure adjacent to heater.

Adjustable set point in flight.
Heater controller set points changed to 12°C in non-operating or safehold Mode. This approach eliminates need for survival heater circuits.



**7.57 cm x 10.48 cm x 2.70 cm and 0.22 kg each. Adjustable set point in flight.*

SXT Heater Controller, Heater and Harness Mass Estimate

	Harness Mass (kg)	Heater Mass (kg)	Thermistor Mass (kg)	Heater Controller* (kg)
Outer Modules	9	14	0.3	40
Middle Modules	6	9	0.2	26
Inner Modules	3	5	0.1	14
Metering Structure	1	9	0.2	5
Subtotal	19	37	0.8	85
Total	142 kg			

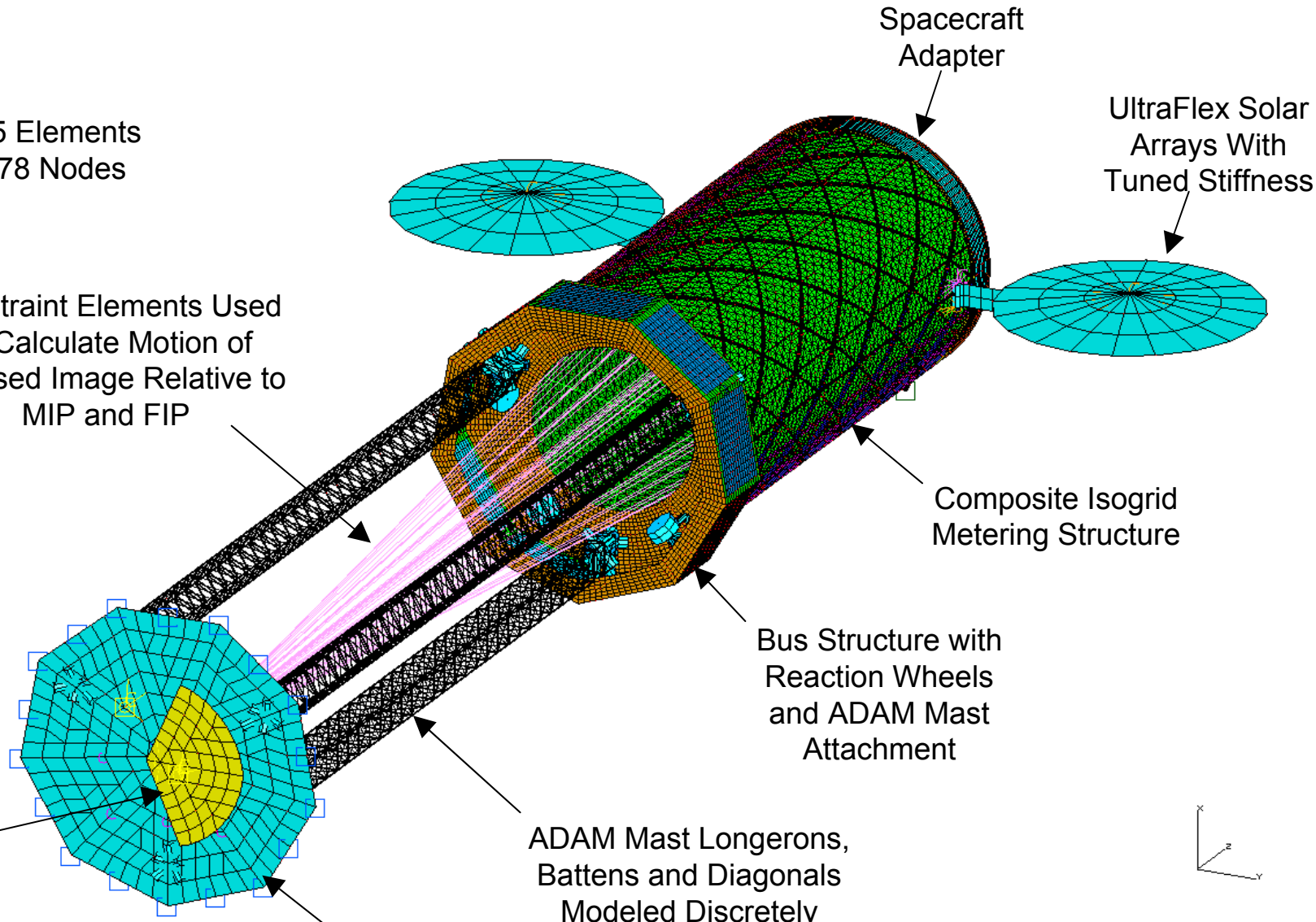
Redundancy included.
*Eliminates temperature control boards in RIU box.

Observatory Finite Element Model

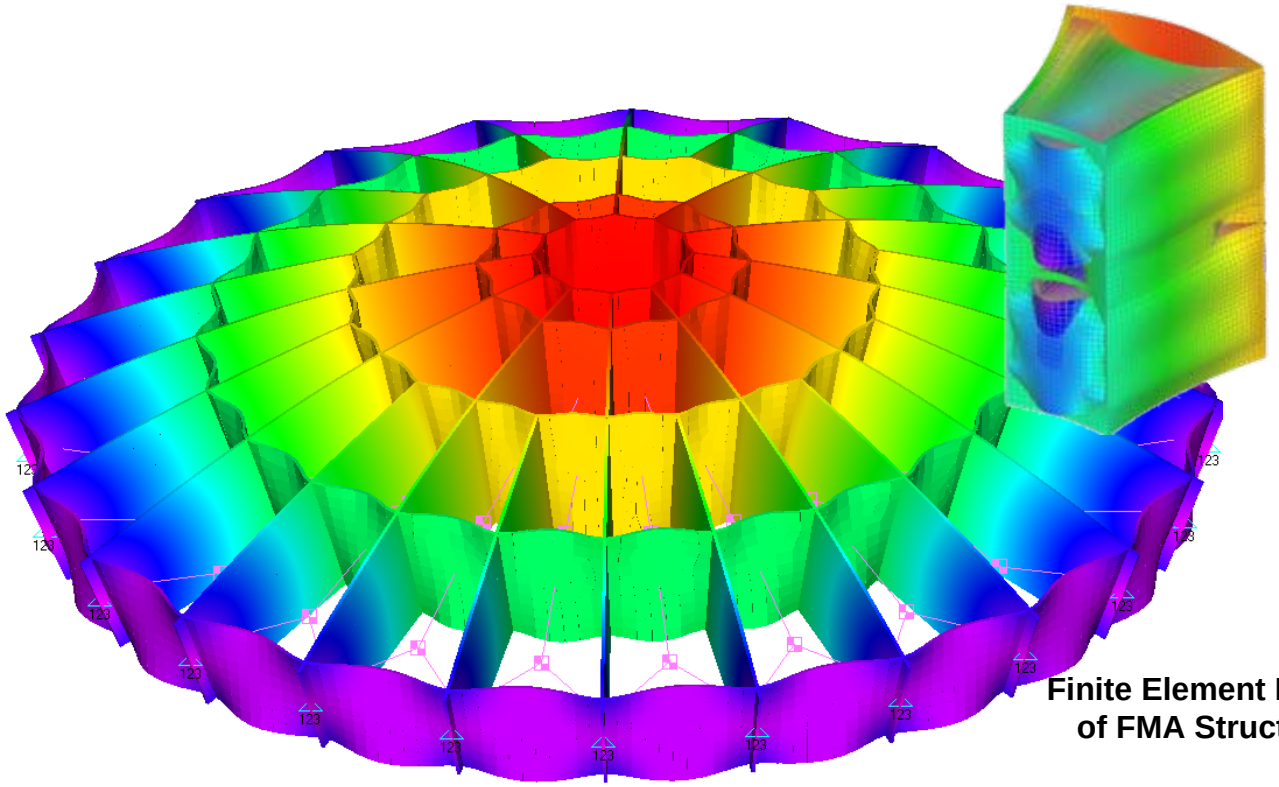
- Pre- and Post-processing Using IDEAS MS12
- Static and Dynamic Model Solution Using NASTRAN NX2.0 and 5.1

Finite Element Model Description

52665 Elements
42978 Nodes



NASA FMA FEM



Finite Element Model of FMA Structure

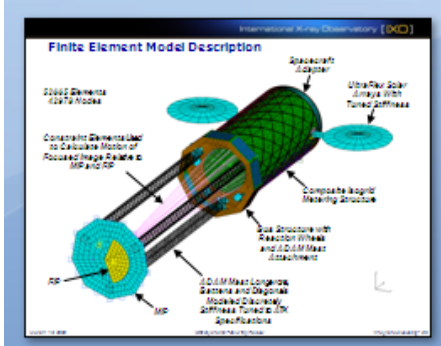
Modal Analysis

Mode Shapes and Frequencies

Mode Number	Frequency (Hz)	Description	
1	0.60	SA Boom Y-Bending, Anti-Symmetric	*Low mass participation*
2	0.60	SA Boom Y-Bending, Symmetric	*Low mass participation*
3	1.04	SV Torsion	
4	1.52	SV Bending (Y) and SA Boom Torsion Sym (1 of 2)	
5	1.54	SV Bending (X) and SA Boom Torsion Antisym (1 of 2)	
6	1.55	SV Bending (Y) and SA Boom Torsion Sym (2 of 2)	
7	1.56	SV Bending (Y) and SA Boom Torsion Sym (2 of 2)	
8	2.21	SA Boom 2nd Y-Bending, Symmetric	
9	2.21	SA Boom 2nd Y-Bending, Anti-Symmetric	
10	7.26	FIP Y-Bending	
11	8.28	SA Boom X-Bending, Symmetric	
12	8.47	SA Boom X-Bending, Anti-Symmetric	
13	8.87	FIP X-Bending	
14	9.34	FIP XY-Bending	
15	10.50	Mast Bending	
16	10.52	Mast Bending	
17	10.70	Mast Bending	
18	10.84	Mast Bending	
19	12.14	MIP Y-rotation	
20	14.79	SV Axial + MIP and FIP X-Rotation	

- 1st Bending and Torsion mode frequencies satisfy IXO's requirements

Mode Shapes and Frequencies



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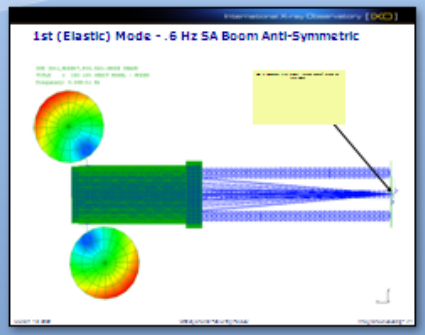

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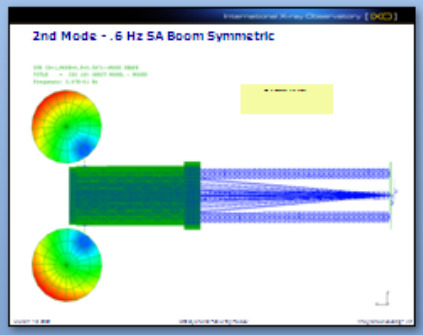

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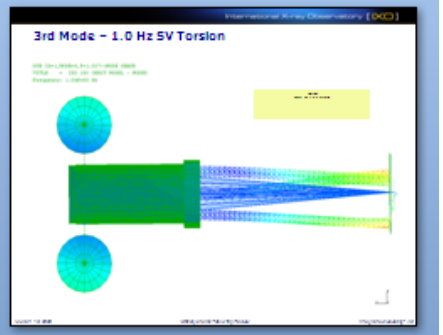

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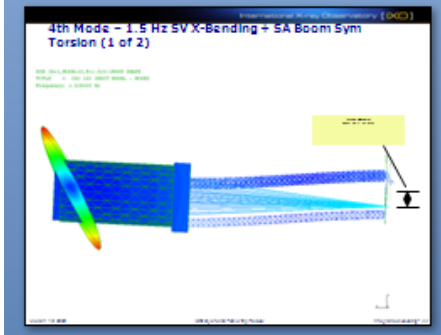

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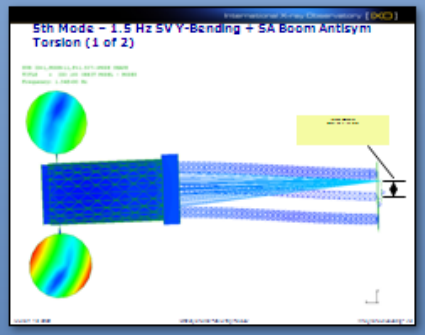

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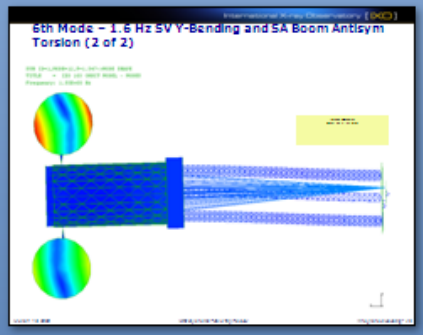

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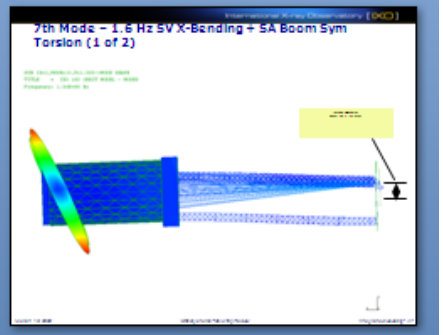

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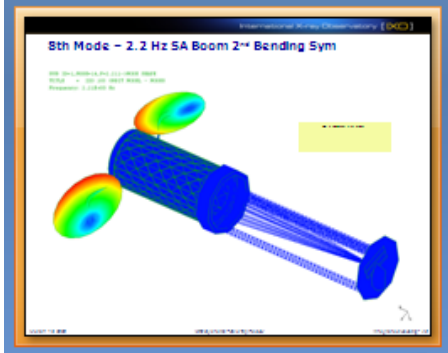

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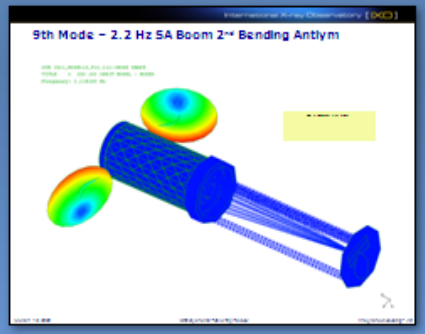

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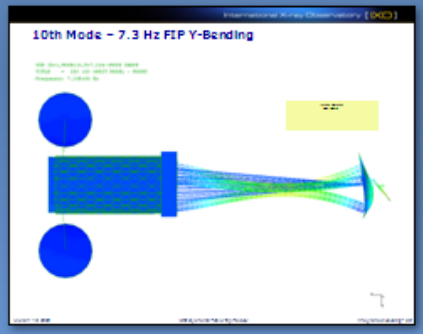

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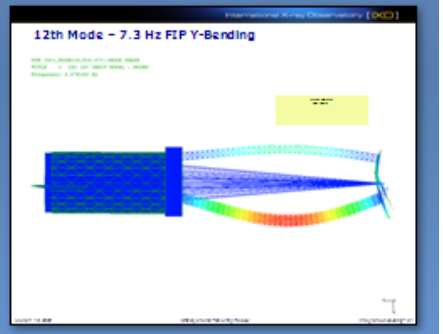

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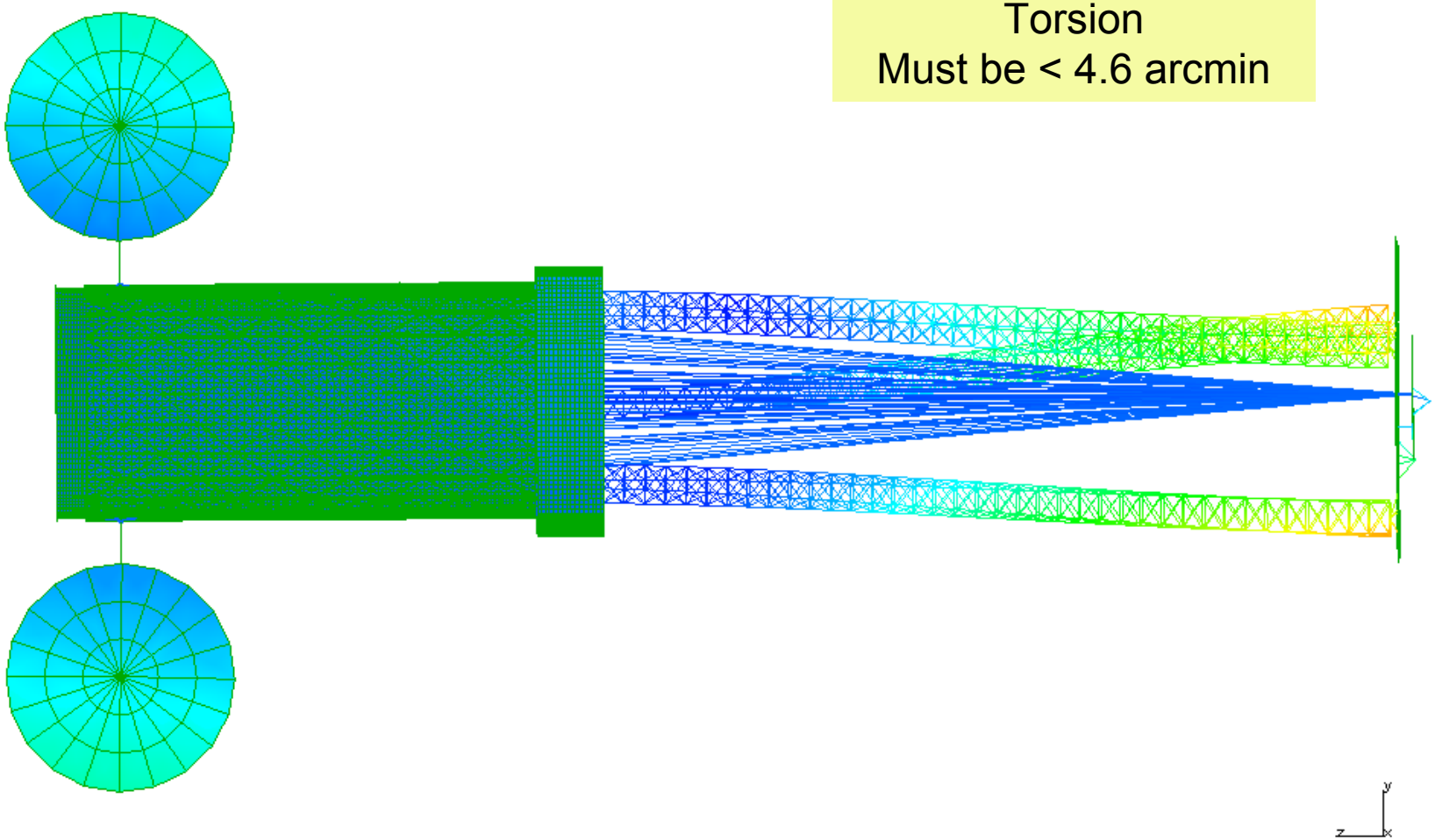
3rd Mode – 1.0 Hz SV Torsion

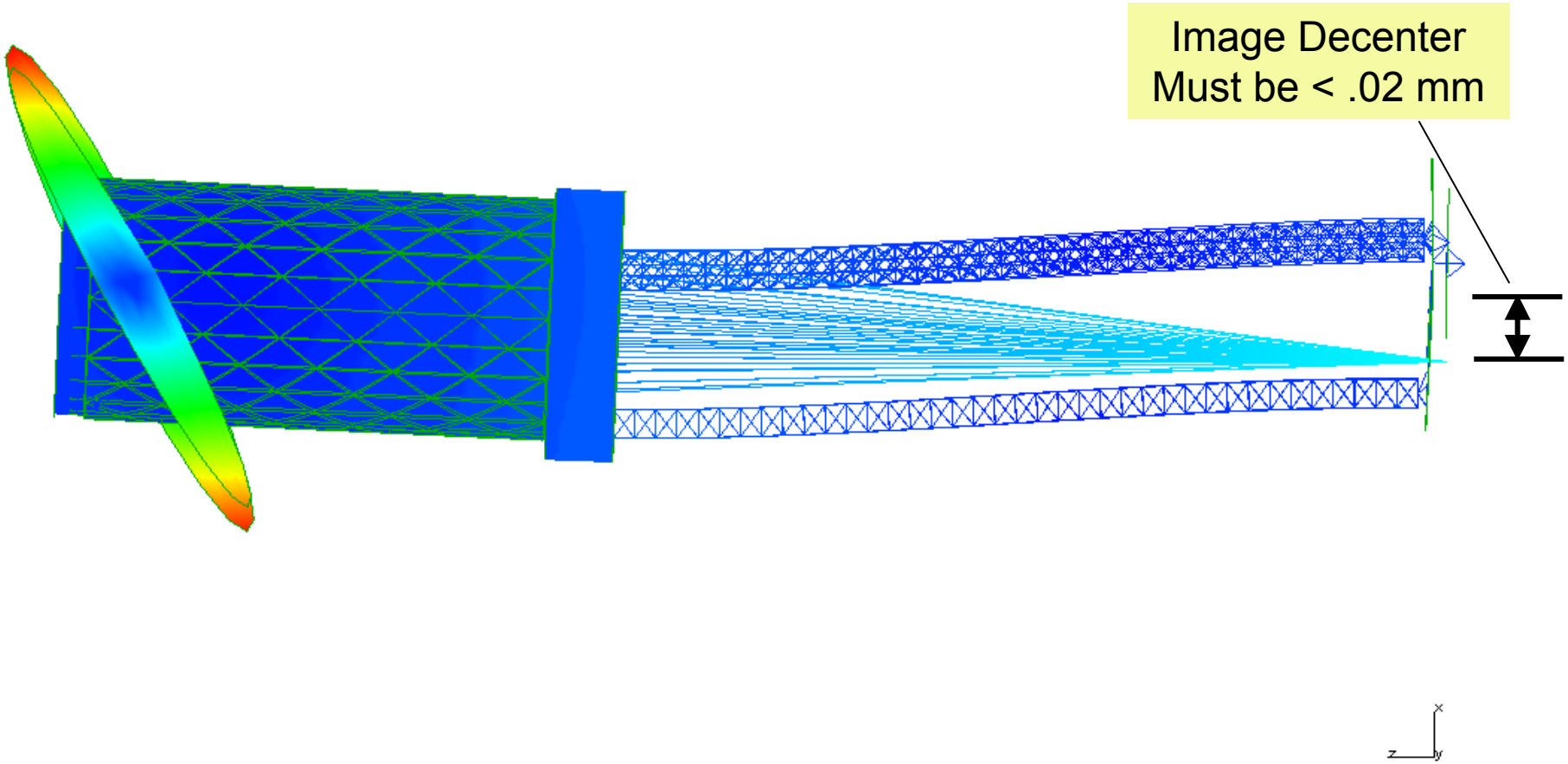
SUB ID=1,MODE=9,F=1.037->MODE SHAPE
TITLE = IXO 1G3 ORBIT MODEL - MODES
Frequency: 1.04E+00 Hz

Torsion
Must be < 4.6 arcmin



4th Mode – 1.5 Hz SV X-Bending + SA Boom Sym Torsion

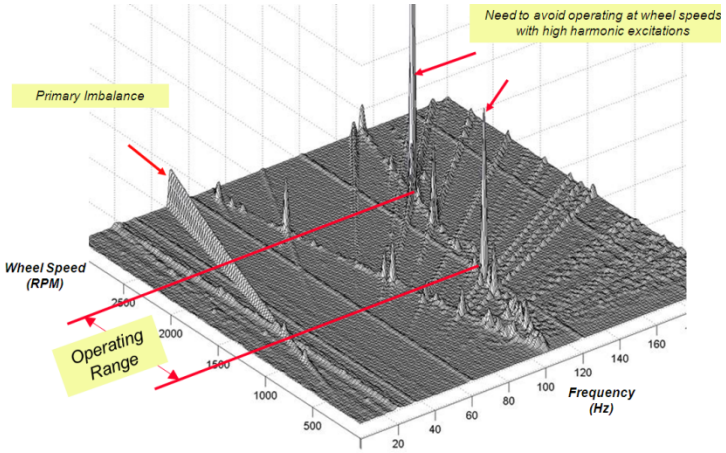
SUB ID=1,MODE=10,F=1.525->MODE SHAPE
TITLE = IXO 1G3 ORBIT MODEL - MODES
Frequency: 1.52E+00 Hz



Jitter Analysis

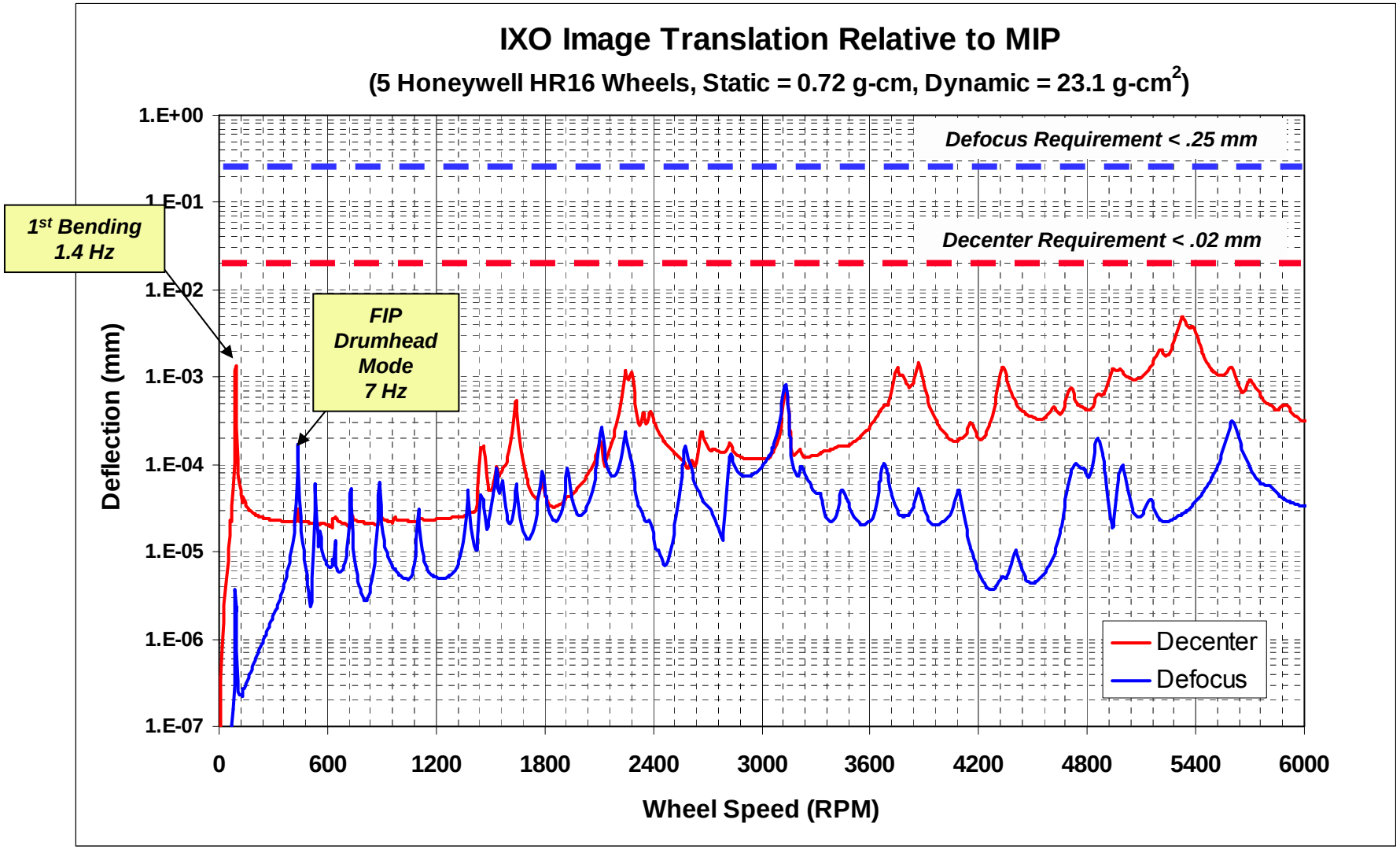
Jitter Analysis Parameters

- 150 N-m-s HR16 Wheel Imbalances (derived from datasheet)
  - Static = .72 g-cm, Dynamic = 23.1 g-cm^2
  - Only primary imbalance considered
  - Refined analysis will include affects of higher harmonics
- Use 0.5% modal damping
- Apply disturbances to all 5 wheels
  - RSS all wheels (conservative: assumes all wheels operate at same speed)
  - Calculate optical element jitter and LOS pointing error versus wheel speed



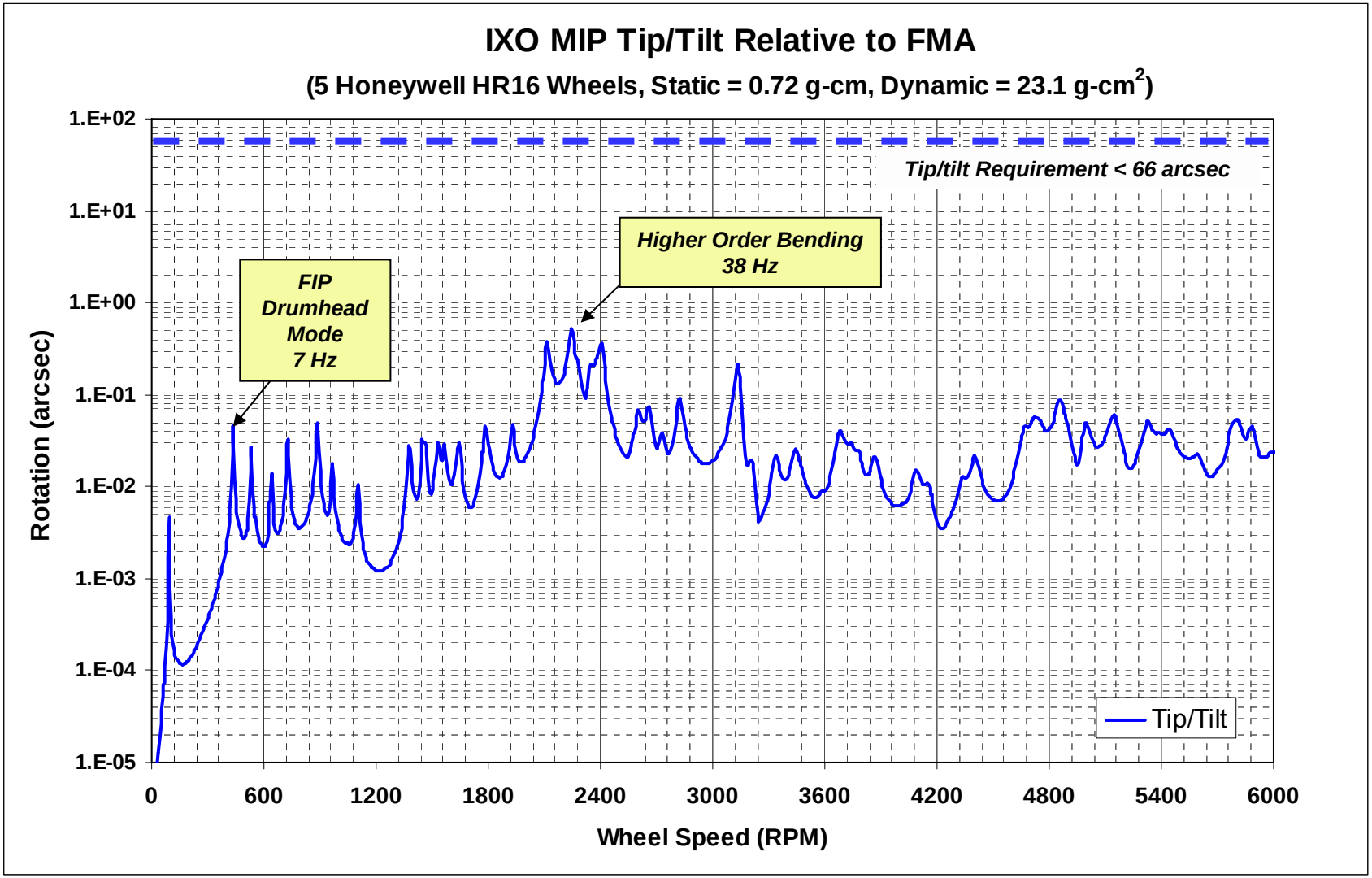
Example Carpet Plot of In-plane Imbalance Forces From HR14 Dynamic Test

Jitter Analysis Results



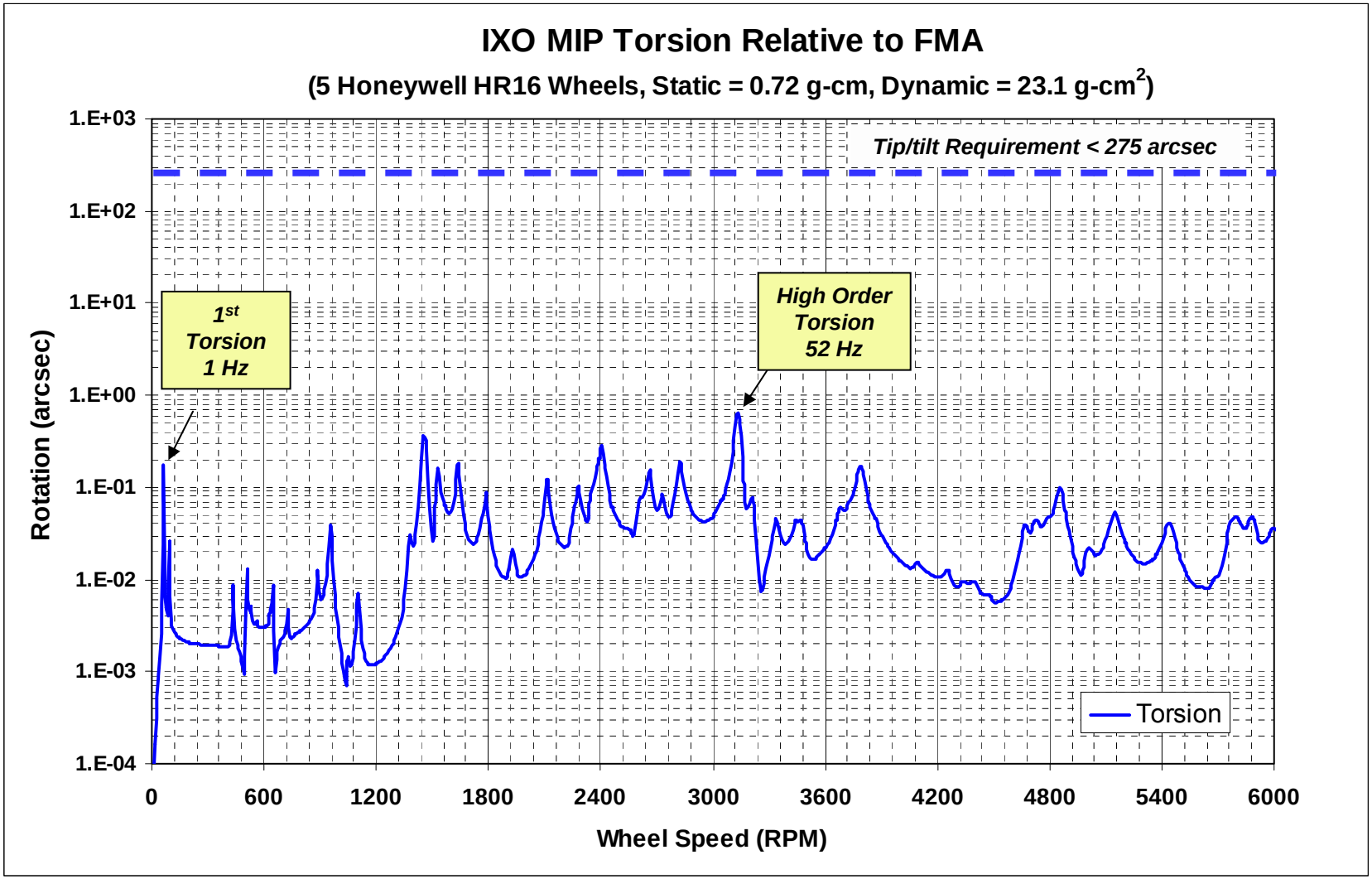
Responses < Requirements

Jitter Analysis Results (Tip / Tilt)



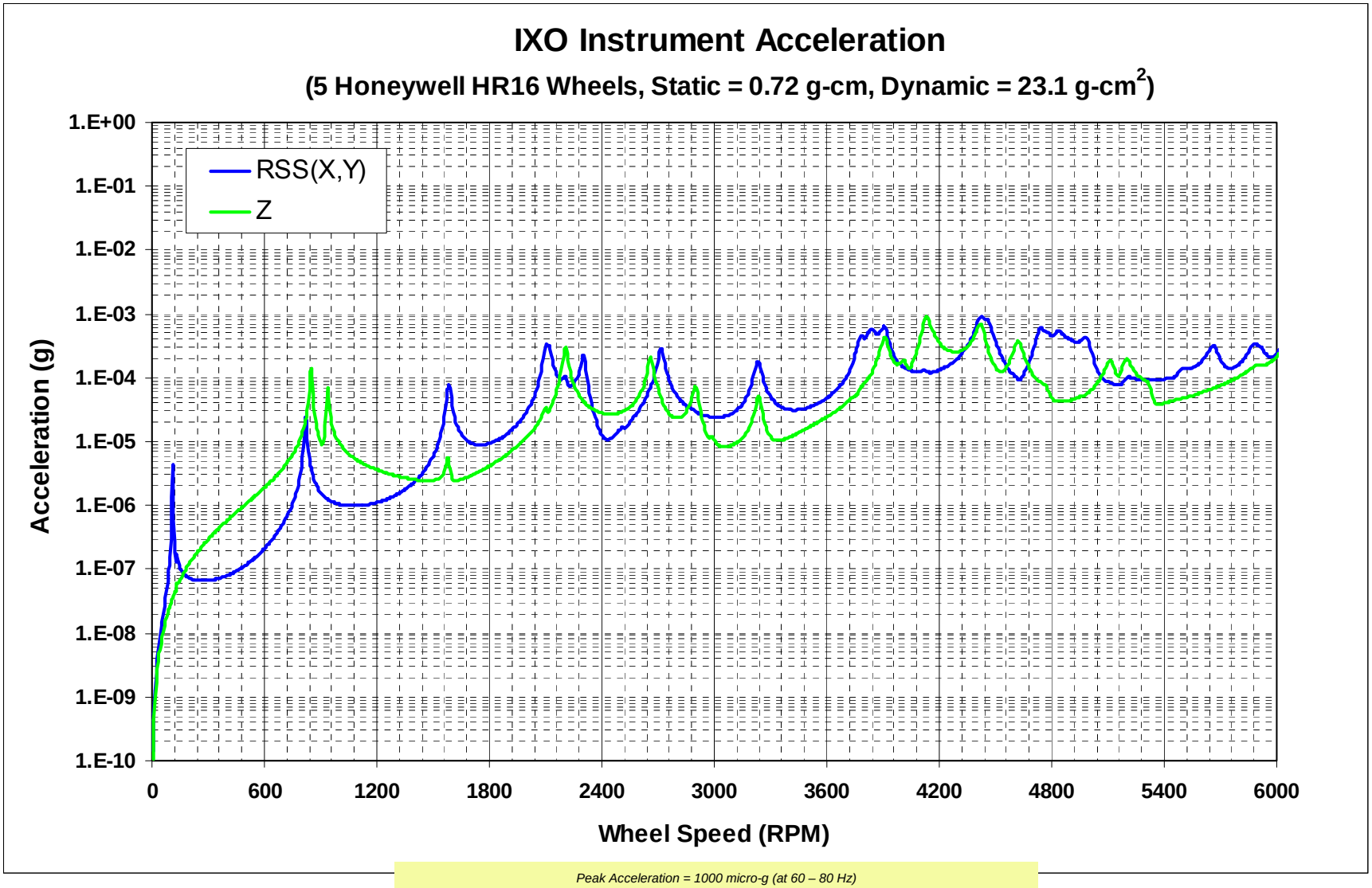
Responses << Requirement

Jitter Analysis Results (Torsion)



Responses << Requirement

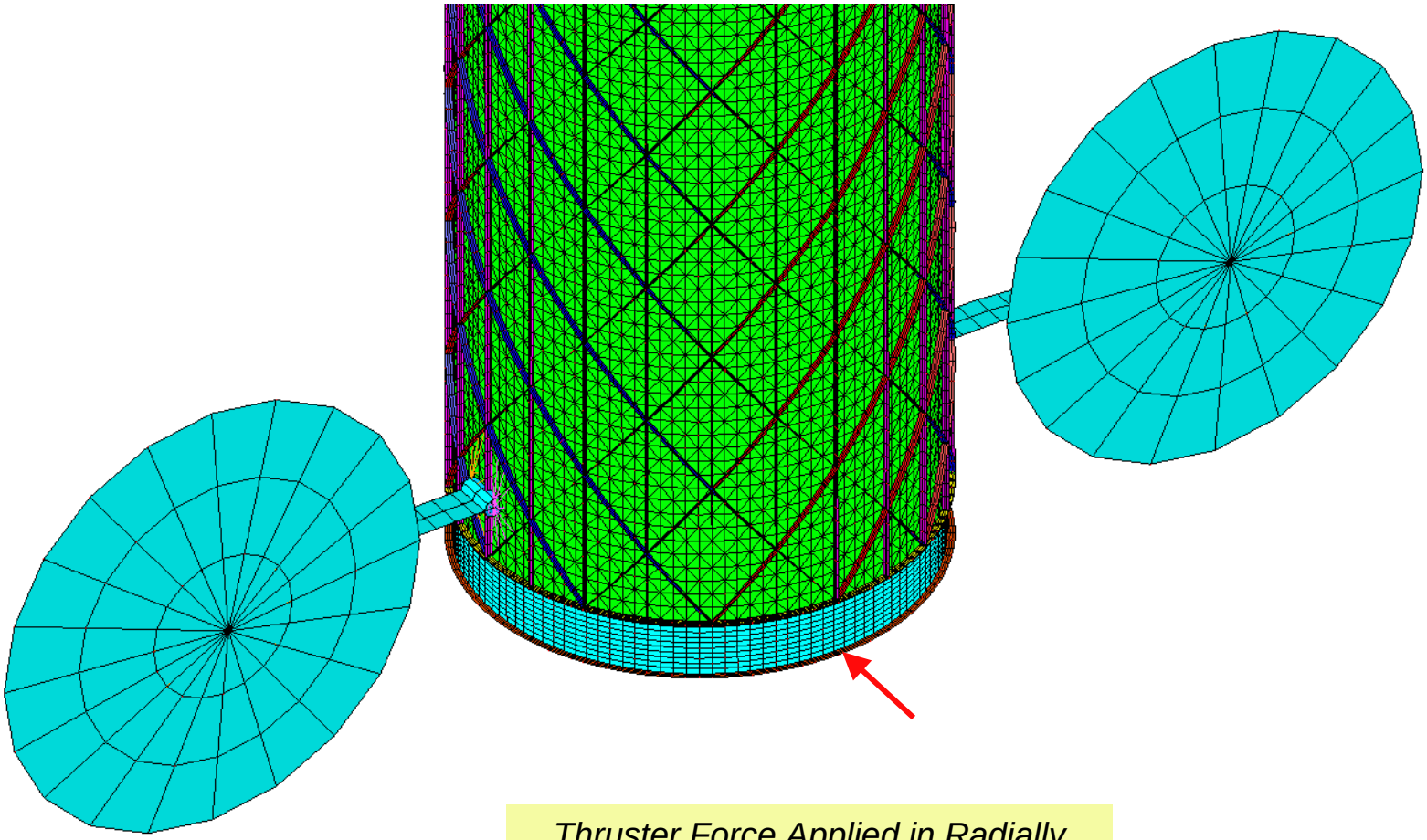
Instrument Accelerations



Peak Acceleration = 1000 micro-g (at 60 – 80 Hz)

Integrated Thruster Firing Analysis

Thruster Force



Thruster Force Applied in Radially Inward Direction to +X Side of Spacecraft Adapter Flange

Impact of Solar Pressure Offload (0.9 N Thruster) Firing

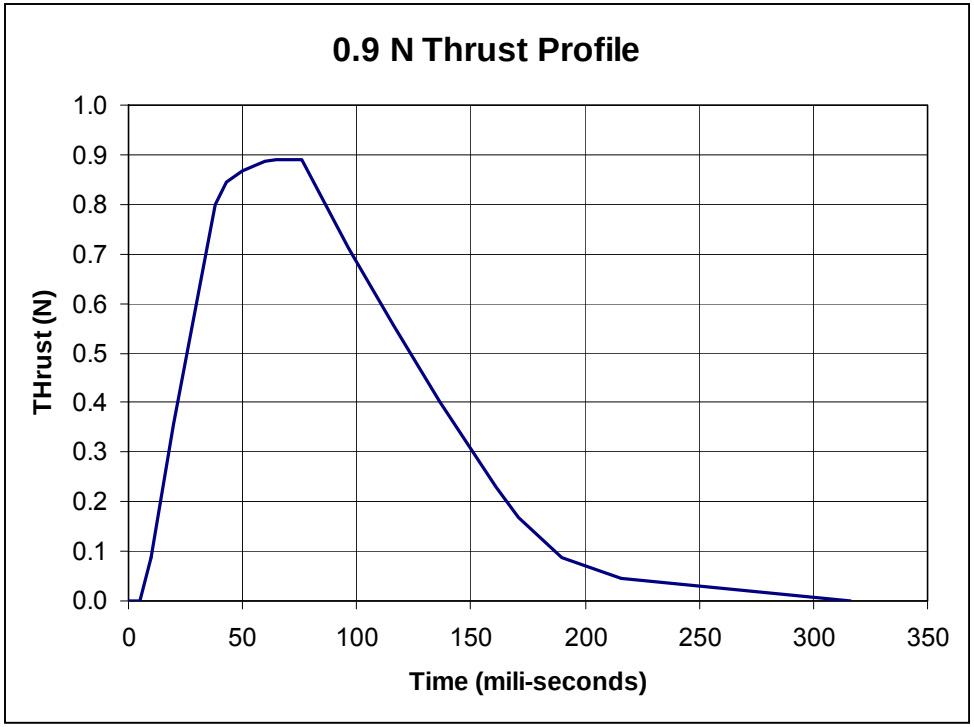
- Use highly reliable MR103H Aerojet thruster used for Voyager and Cassini

- Attitude Deviation versus Pulse Length
  - 0.11 s burn every 18 minutes: 0.165 arcsec deviation

- Number of 0.11 s Thruster Firings:
  - 300,000 over 10 Years (once per 18 min)
    - Voyager had 500,000 burns from single thruster, using same thruster
  - Total amount of propellant: 15 kg

- Assumes IXO config with two 3.35 m dia Circular Ultraflex Solar Arrays

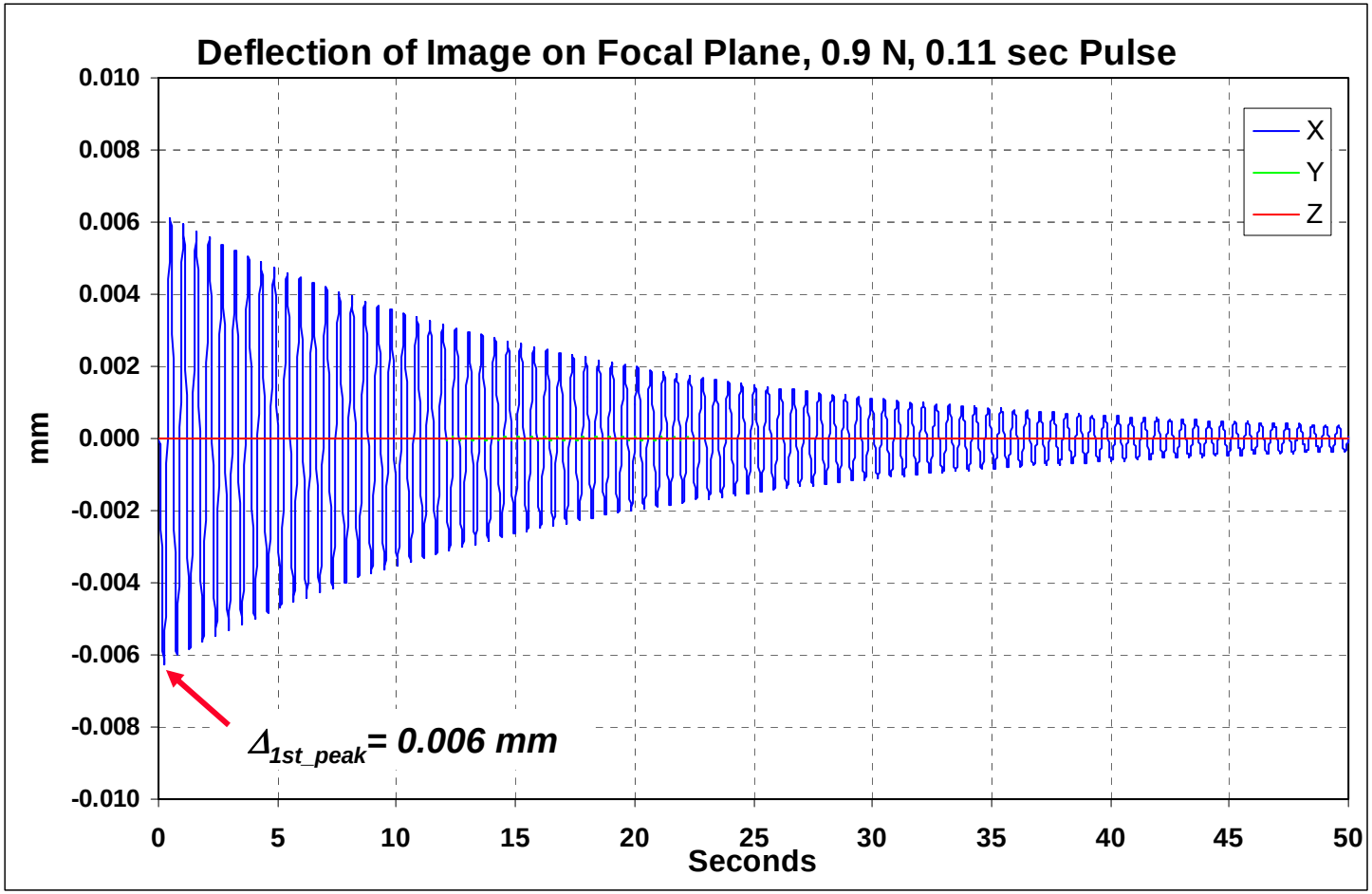
Thruster Pulse and Model Parameters



Total Impulse = 0.1 N-s
Derived from Astrolink jitter analysis profile

- **Modal damping = .5% of critical damping**
- **232 modes included in solution space (0 to 150 Hz range)**
- **2500 time steps at .001 second per step**

Vibration Decay



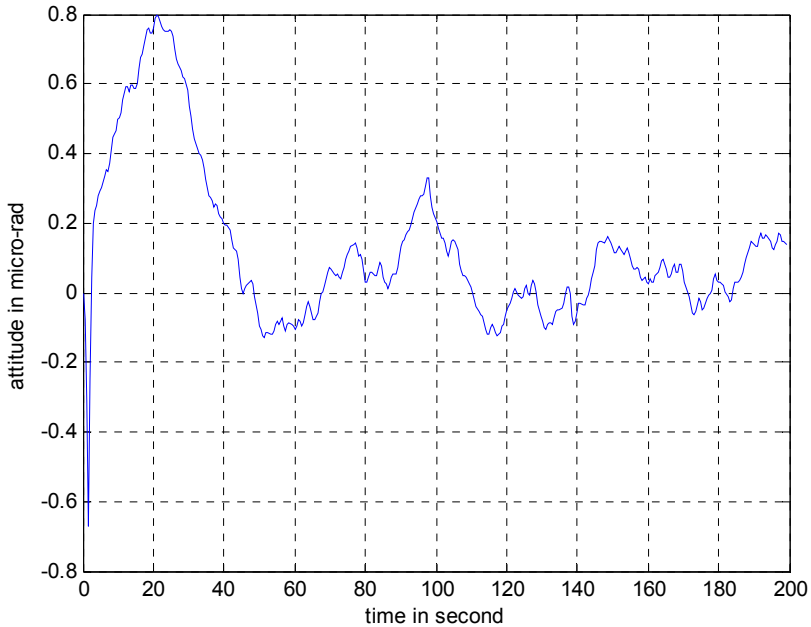
$$\frac{\Delta_{nth_peak}}{\Delta_{1st_peak}} = e^{-2\pi n\xi/(1-\xi^2)^{1/2}} \Rightarrow \Delta_{peak_at_time_t} = 0.006e^{-.0575t}$$

Deflection Decays to less than .001 mm after 30 seconds

Integrated FEM + Control System Result

Temporary Attitude Deviation due to 0.9 N Thruster Firing

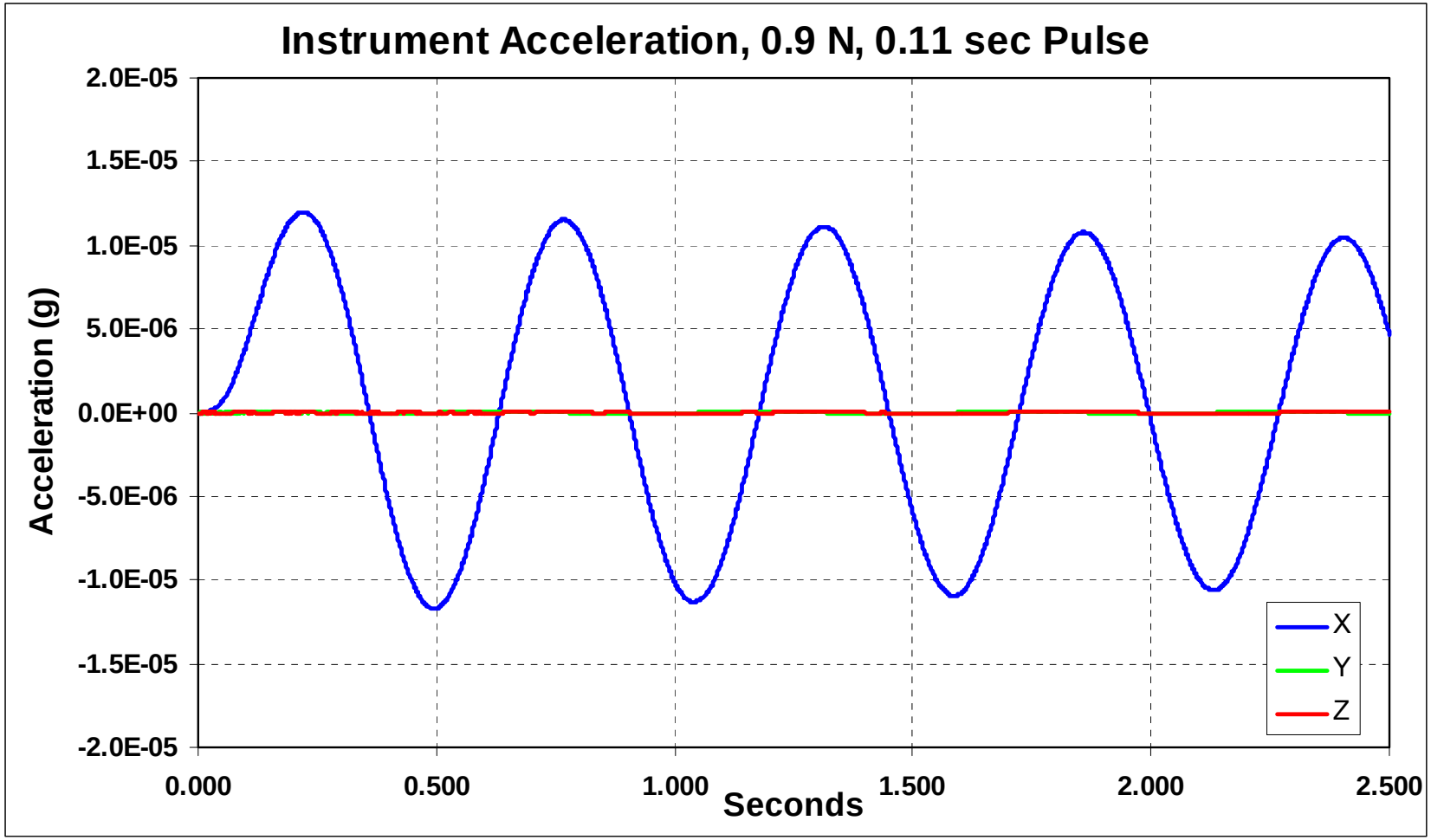
- 0.9 N Thruster on for 0.11 s; generates 0.1 Ns impulse and 0.62 Nms angular momentum delta
- RWL feed forward of -0.2 Nm for 3.1 seconds
- Thruster firing centered relative to 3.1 second RWL feed forward period



- Resulting attitude excursion about Y axis: 0.165 arcsec

Integrated FEM + Control System Result

Accelerations due to 0.9 N Thruster Firing



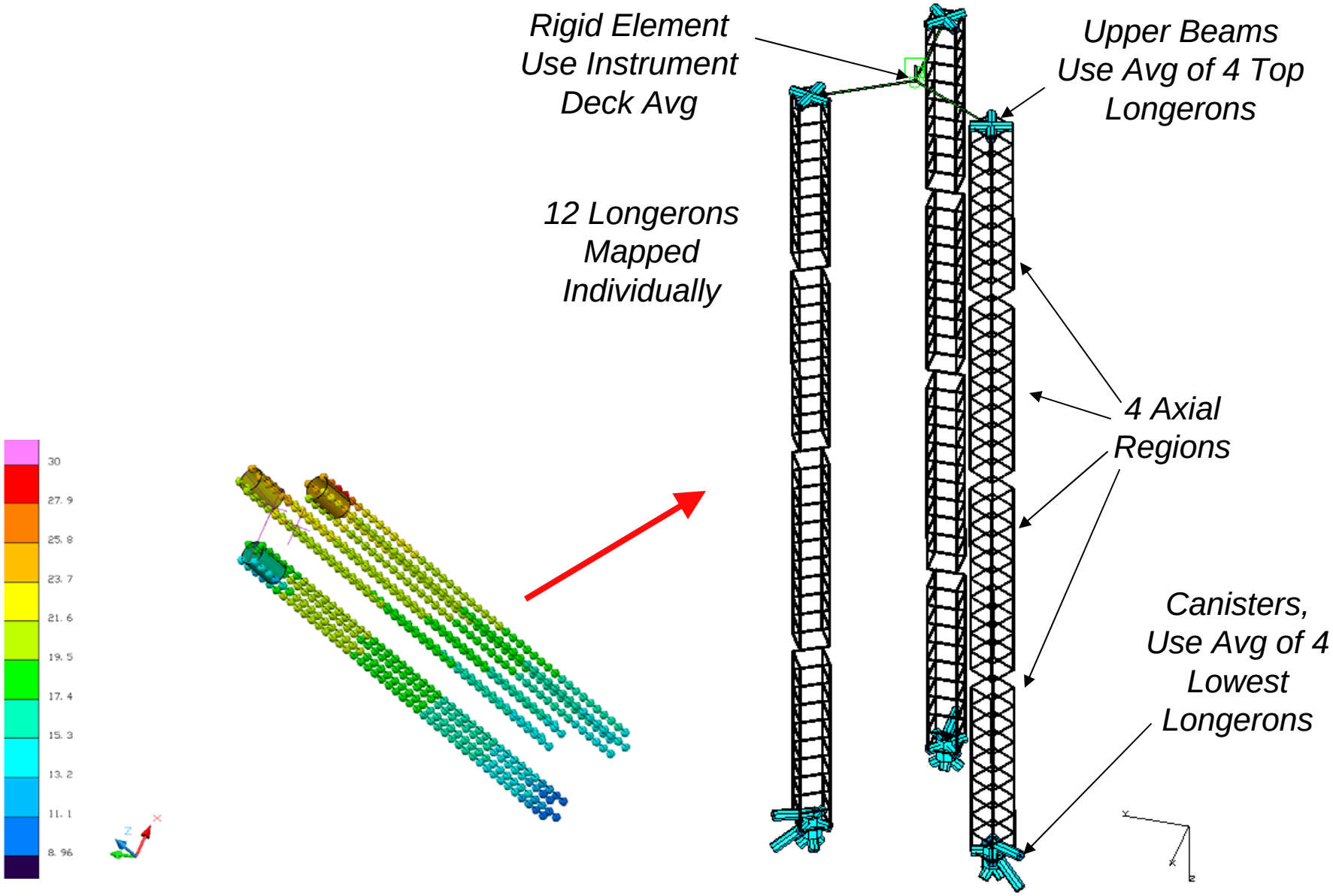
Peak Acceleration = 12 micro-g

Integrated Thermal Distortion Analysis

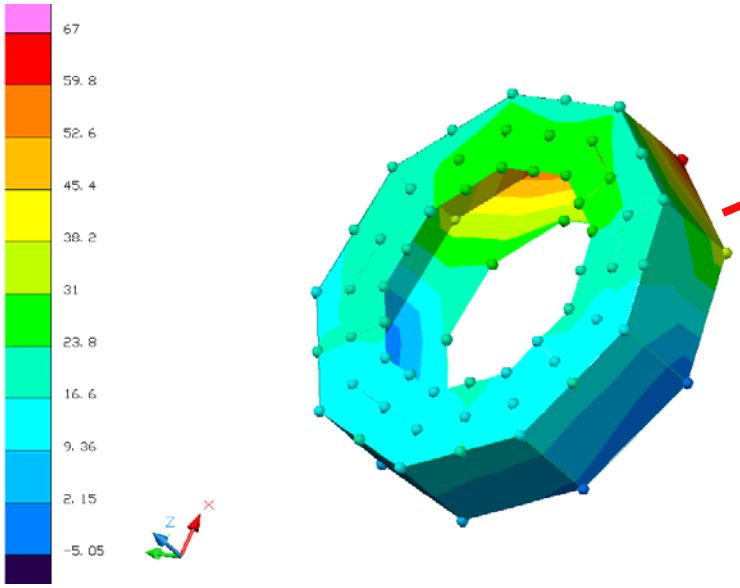
Temperature Mapping

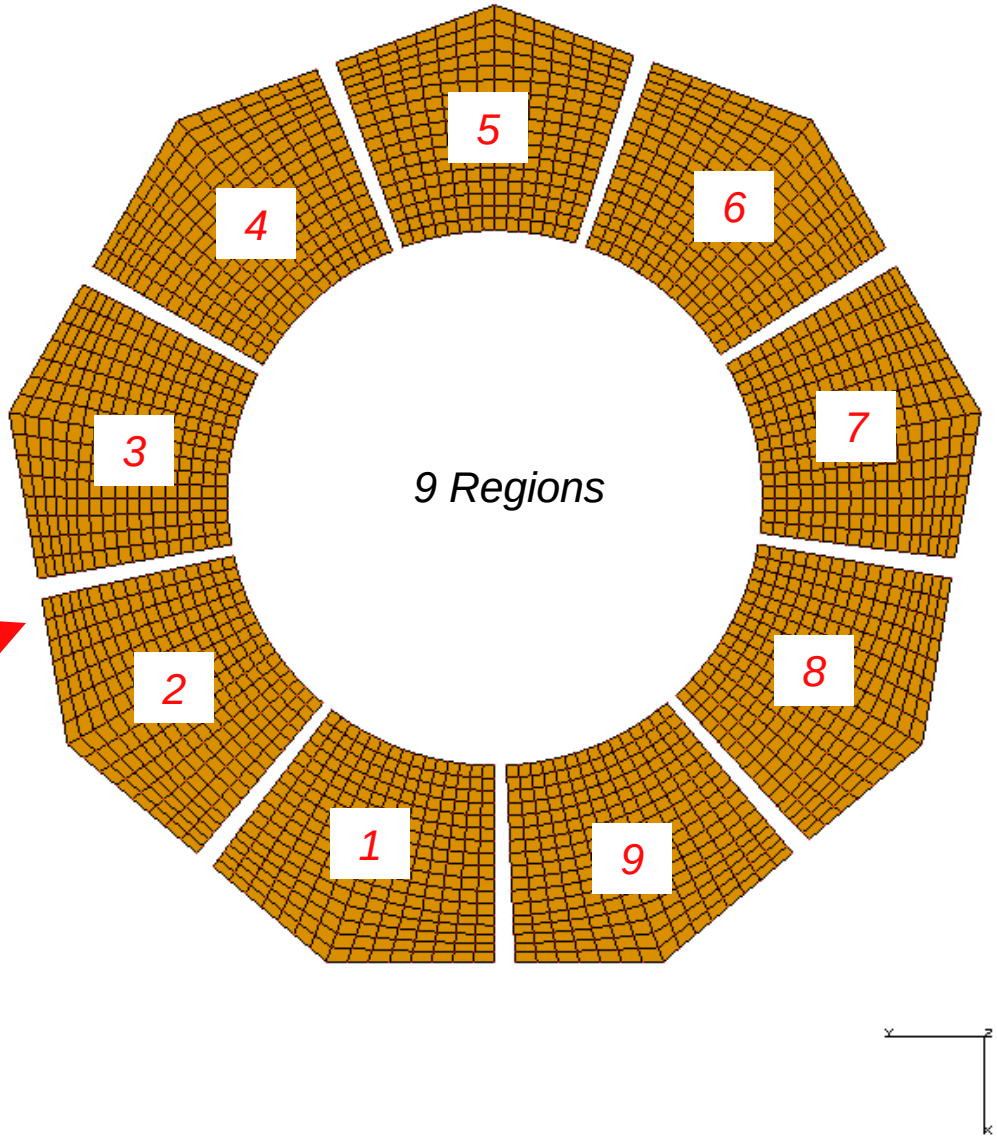
- Temperatures from the thermal analysis model are mapped onto the structural finite element model
- Temperature cases are analyzed for three SV orientations
  - 0 degrees pitch, 0 degrees roll
  - -20 degrees pitch, 20 degrees roll
  - +20 degrees pitch, 20 degrees roll
- Changes in deflection due to slew maneuvers are determined by taking the differences between the three cases

Mast LongeronsTemperature Mapping

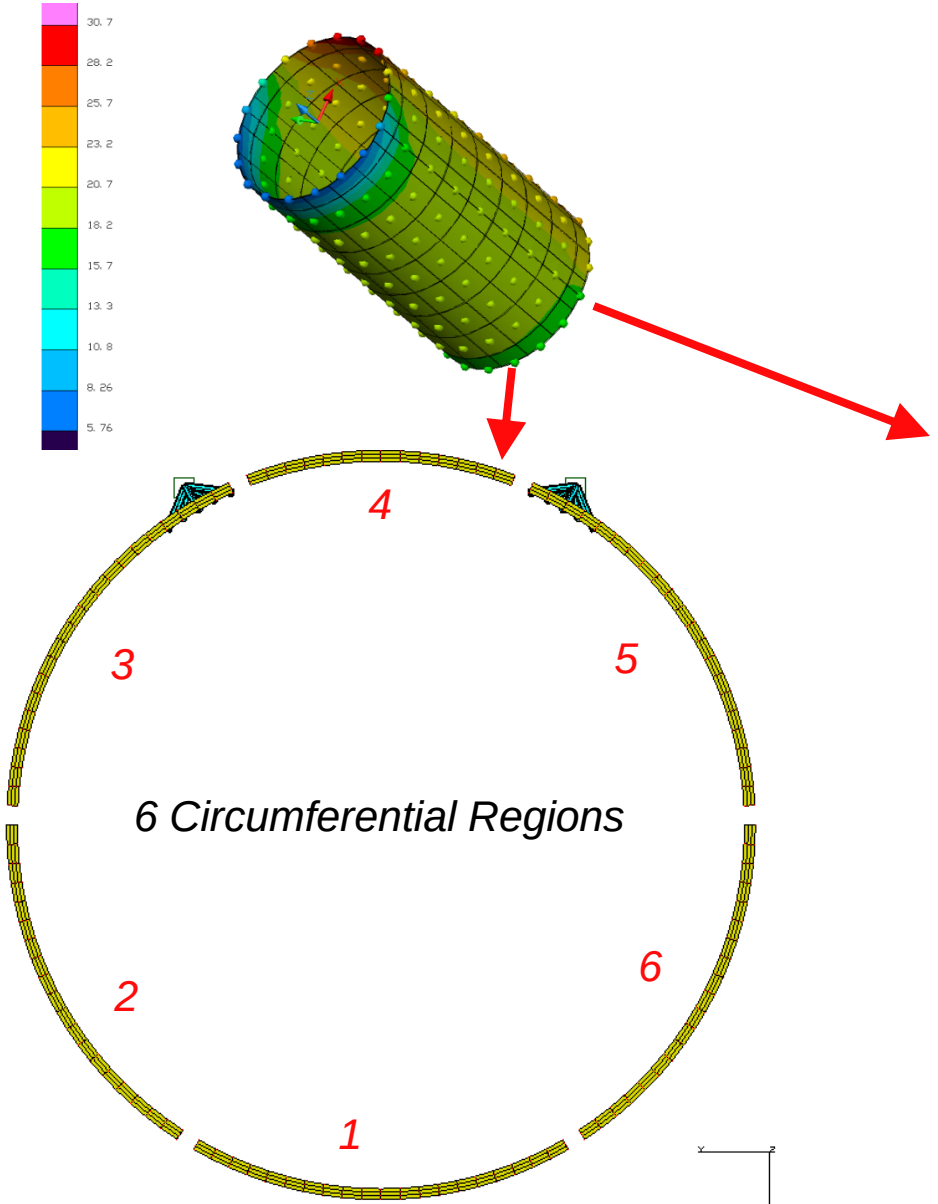


Bus Aft Deck Temperature Mapping

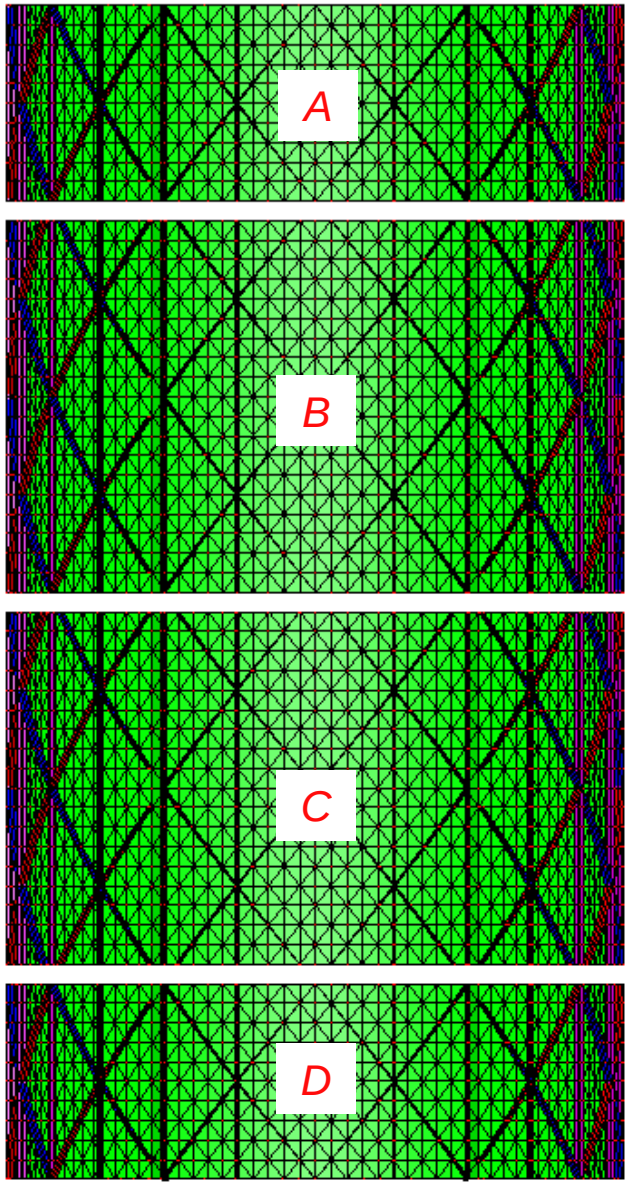




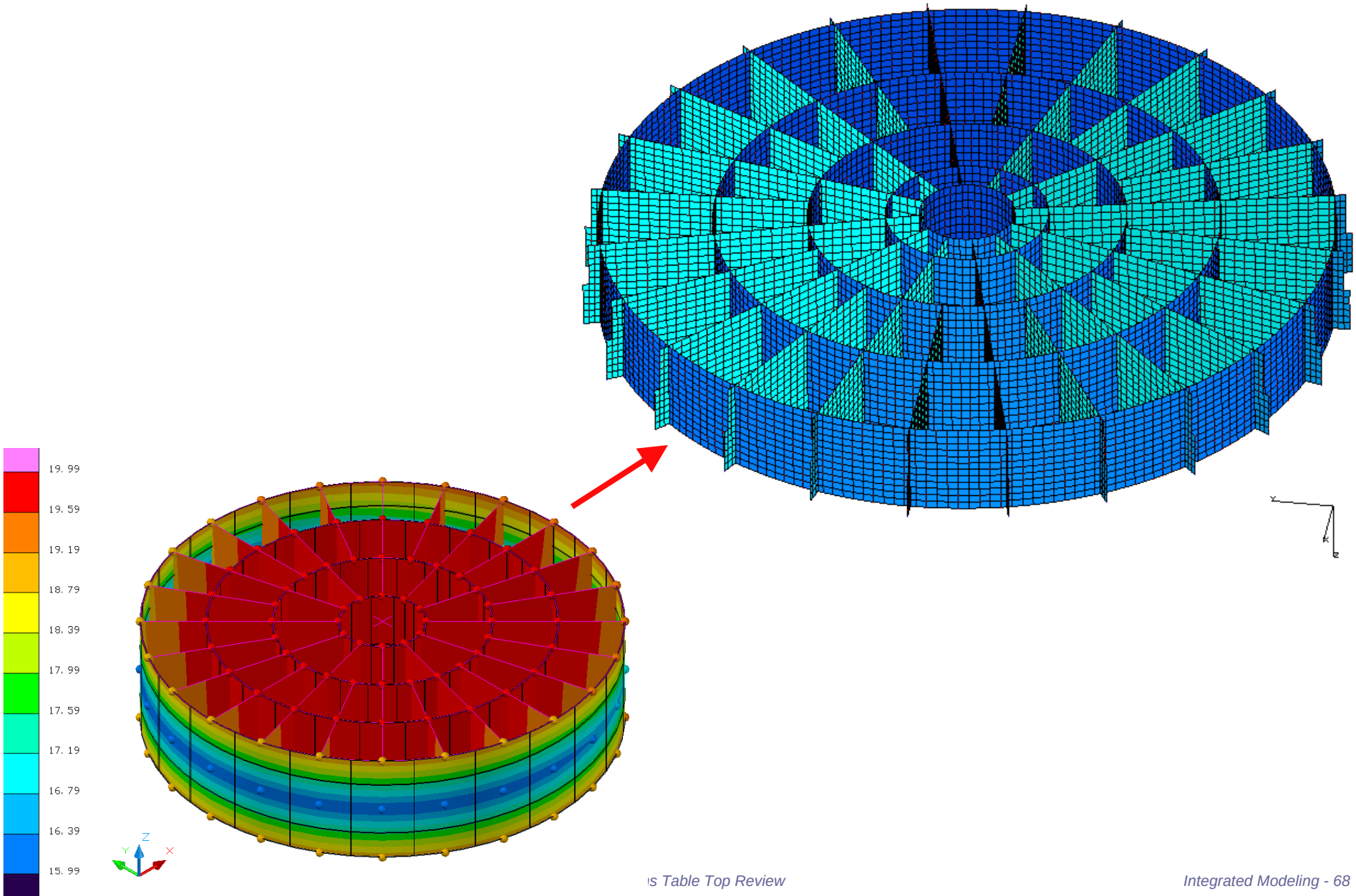
FMS Temperature Mapping



4 Longitudinal Regions



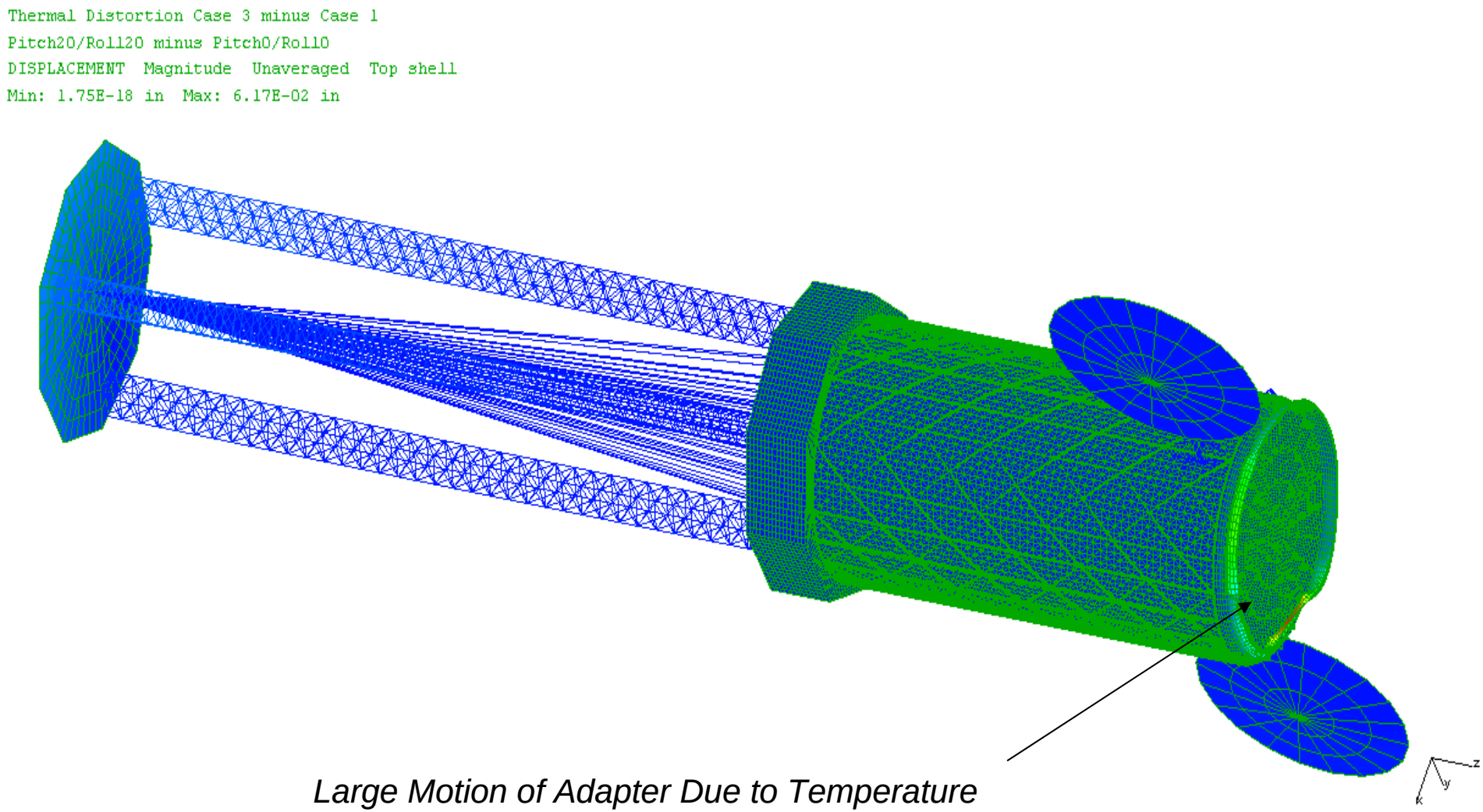
FMA Temperature Mapping



Thermal Distortion Model Configuration

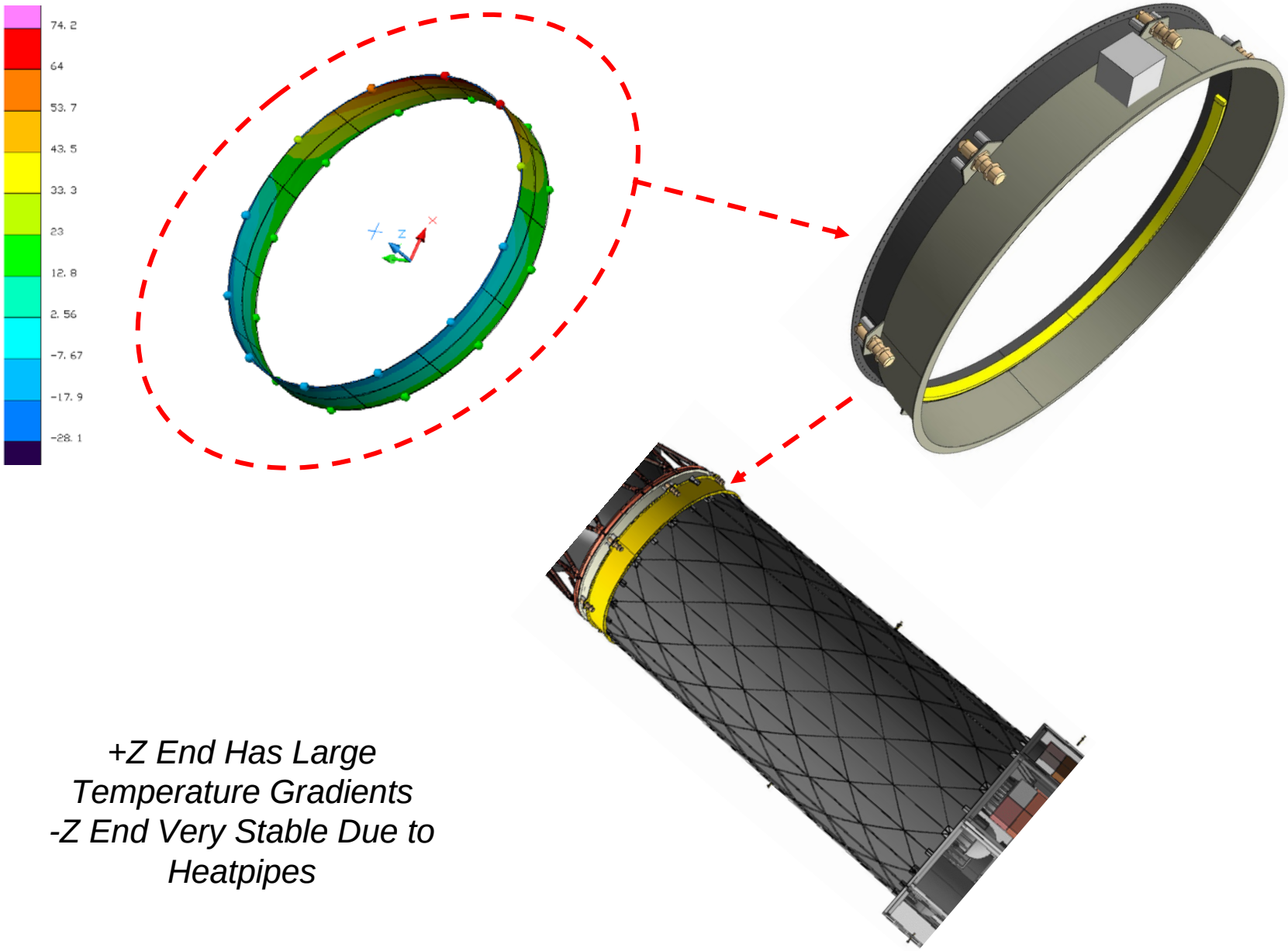
- Model Kinematically Restrained at FMA
- Material Properties (Coef. Of Thermal Expantion, CTE)
  - Aluminum, +22.5E-6 /degC
    - Spacecraft Adapater, Instrument FIP
  - M55J QI, -0.3E-6 /degC
    - FMA, Isogrid
  - M55J QI Facesheet on Aluminum Honeycomb, +0.5E-6 /degC
    - Bus structure
  - ADAM masts, +0.34E-6 /degC (from ATK tests of similar masts)

Slew: Pitch-0/Roll-0 to Pitch-20/Roll-20



Large Motion of Adapter Due to Temperature Gradients at Aft End of Adapter
Other Deflections Relatively Small

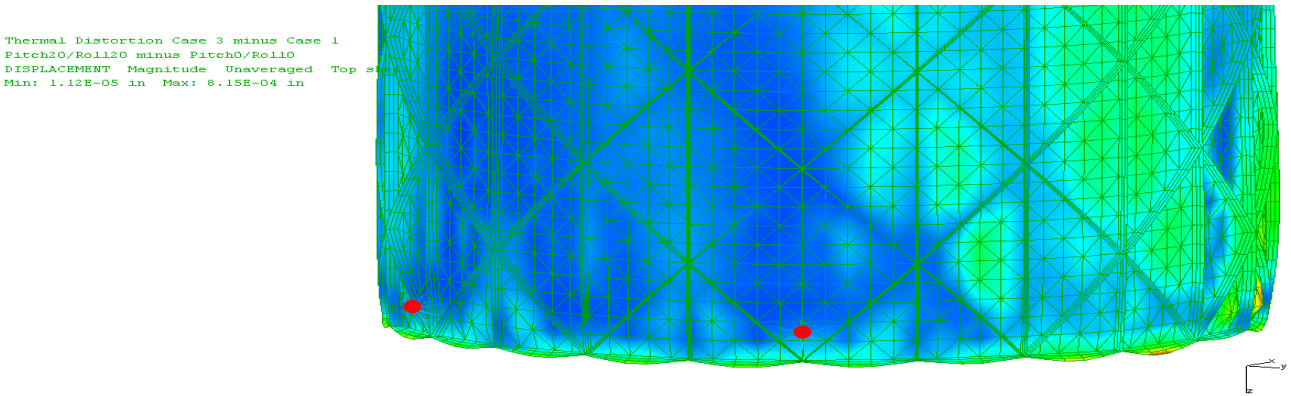
Aluminum Payload Adapter Temperatures



+Z End Has Large Temperature Gradients
-Z End Very Stable Due to Heatpipes

Integrated Thermal Distortion Analysis Result

- **Bottom of FMS is "pulled in" by aluminum payload adapter, and that causes rotation of star trackers > 2 arcsec if mounted on isogrid structure**



Slew From Pitch_0/Roll_0 to Pitch_20/Roll_20

	DISPLACEMENTS						
LOCATION	POINT ID.	X (mm)	Y (mm)	Z (mm)	RX (asec)	RY (asec)	RZ (asec)
FMA Avg	20096	0.0000	0.0000	0.0000	0.000	0.000	0.000
TAD Corner Cube	60857	-0.0001	-0.0002	0.0000	0.003	0.000	-0.015
+Y Star Tracker	60858	0.0036	0.0002	0.0018	1.237	2.688	-0.319
-Y Star Tracker	60864	0.0018	0.0029	0.0022	-1.738	2.312	-0.180
Image on Focal Plane		0.0052	0.0776	-0.0074	1.097	-0.079	0.199

Slew From Pitch_0/Roll_0 to Pitch_-20/Roll_20

	DISPLACEMENTS						
LOCATION	POINT ID.	X (mm)	Y (mm)	Z (mm)	RX (asec)	RY (asec)	RZ (asec)
FMA Avg	20096	0.0000	0.0000	0.0000	0.000	0.000	0.000
TAD Corner Cube	60857	-0.0002	-0.0003	0.0000	0.003	0.000	-0.009
+Y Star Tracker	60858	0.0020	0.0015	0.0010	-0.067	1.110	0.086
-Y Star Tracker	60864	0.0001	0.0021	0.0001	-0.335	0.268	-0.308
Image on Focal Plane		0.0027	0.1018	-0.0134	1.314	-0.035	0.245

- **Focal Plane Image Deflections Within Acceptable Limits**
- **Star Tracker Rotations Excessive When Located on Isogrid**
- **Resolution: Star Trackers moved to center of FMA (see next slide)**

Thermal Distortion Results: Requirements Met with Star Tracker Moved on FMA

Slew From Pitch_0/Roll_0 to Pitch_20/Roll_20

	DISPLACEMENTS					
LOCATION	X (mm)	Y (mm)	Z (mm)	RX (asec)	RY (asec)	RZ (asec)
FMA Avg	0.0000	0.0000	0.0000	0.000	0.000	0.000
TAD Corner Cube	-0.0001	-0.0002	0.0000	0.003	0.000	-0.015
+Y Star Tracker	0.0000	0.0000	0.0000	0.000	0.000	0.000
-Y Star Tracker	0.0000	0.0000	0.0000	0.000	0.000	0.000
Image on Focal Plane	0.0052	0.0776	-0.0074	1.097	-0.079	0.199

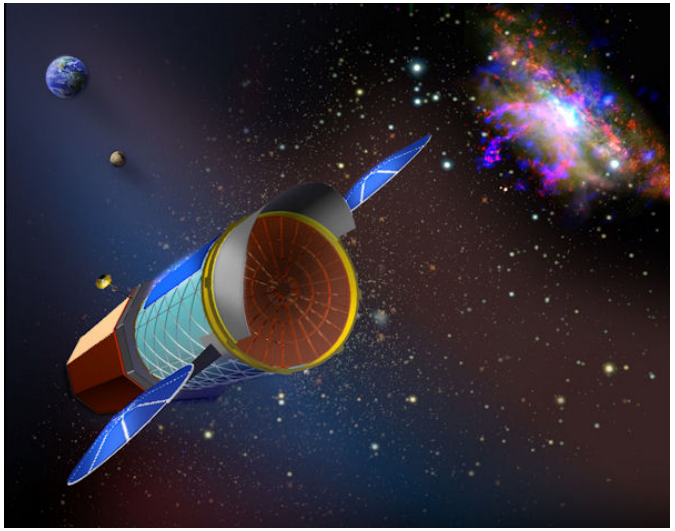
Slew From Pitch_0/Roll_0 to Pitch_-20/Roll_20

	DISPLACEMENTS					
LOCATION	X (mm)	Y (mm)	Z (mm)	RX (asec)	RY (asec)	RZ (asec)
FMA Avg	0.0000	0.0000	0.0000	0.000	0.000	0.000
TAD Corner Cube	-0.0002	-0.0003	0.0000	0.003	0.000	-0.009
+Y Star Tracker	0.0000	0.0000	0.0000	0.000	0.000	0.000
-Y Star Tracker	0.0000	0.0000	0.0000	0.000	0.000	0.000
Image on Focal Plane	0.0027	0.1018	-0.0134	1.314	-0.035	0.245

- **Focal Plane Image Deflections Within Acceptable Limits**

IXO Table Top Review

2009 03 12
NASA GSFC, Bldg 23, Room C130D



Flight Dynamics

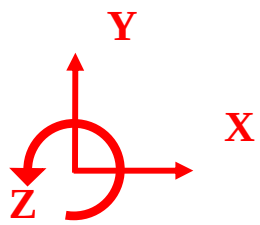
Michael Mesarch
NASA / GSFC
Navigation & Mission Design Branch
Code 595

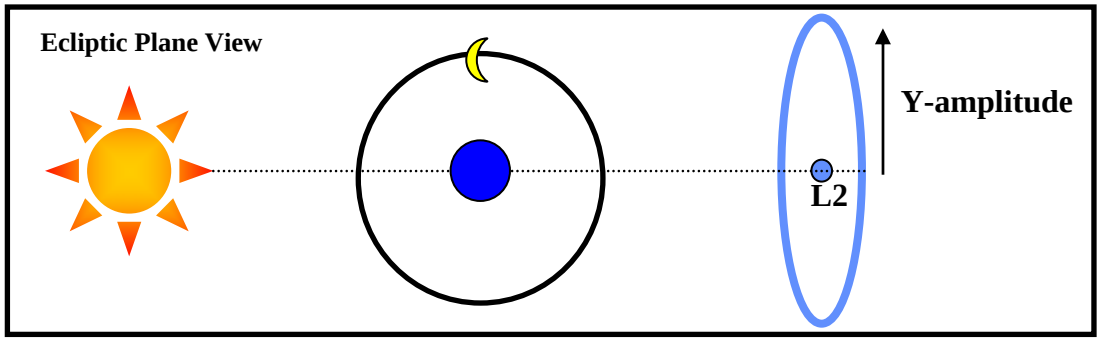
NASA\GSFC Libration Point Heritage

- The NASA\GSFC Navigation and Mission Design Branch (Code 595) has the expertise and experience needed in the areas of trajectory design, navigation analysis, and operations for IXO
- Code 595's libration point experience:
  - L1: International Sun-Earth Explorer 3 (ISEE-3) – 1978
  - L1/L2: WIND – 1994 (support is ongoing)
  - L1: Solar and Heliospheric Observatory (SoHO) – 1995 (support is ongoing)
  - L1: Advanced Composition Explorer (ACE) – 1997 (support is ongoing)
  - L2: Wilkinson Microwave Anisotropy Probe (WMAP) - 2001 (support is ongoing)
  - L2: Currently, Code 595 is the lead for trajectory design and navigation for the James Webb Space Telescope (JWST).
- IXO will be very similar in architecture to JWST (e.g. requiring a sequential orbit determination process due to the frequent momentum unloads)
  - Code 595 involvement in IXO will be able to leverage greatly off the experience gained through the current JWST support

IXO Flight Dynamics Requirements

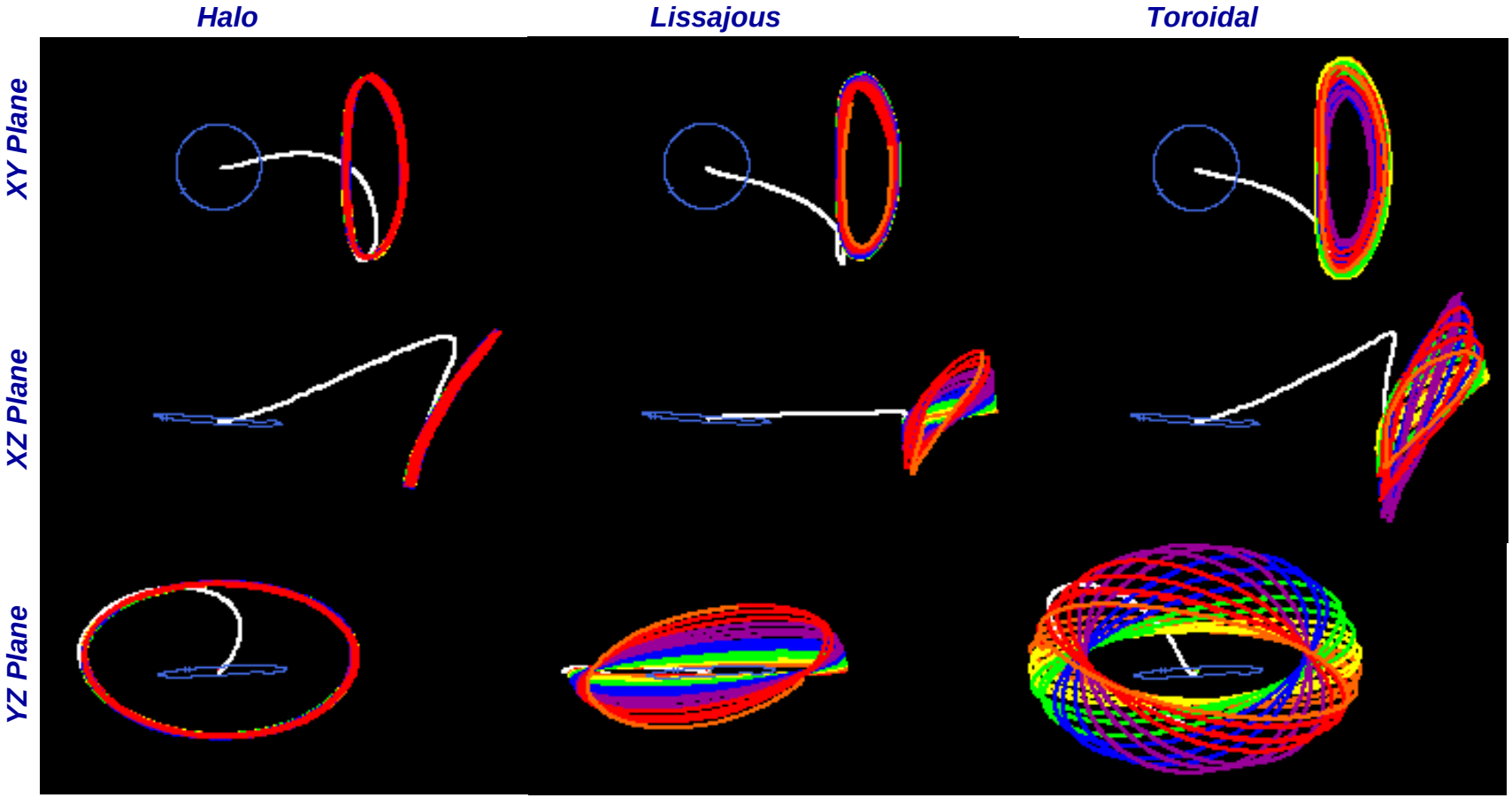
- Launch from the Eastern Range (KSC) on a direct transfer to a Sun-Earth L2 libration point orbit no earlier than December, 2020
- Launch energy: -0.5 km^2/s^2 (upper limit)
- Launch Vehicle: Atlas-V 551 or Ariane 5
- Lifetime: 5 years (10 years consumables)
  - Orbit selected to eliminate all eclipses (including lunar)
- L2 Mission Orbit Size:
  - Y Amplitude ≤ 800,000 km (in ecliptic plane perpendicular to Earth-Sun line)
  - Z Amplitude ≤ 500,000 km (out of ecliptic plane)
  - This size is identical to the requirements for JWST and does not require an orbit insertion maneuver upon arrival to the L2 region
  - Size restriction is consistent with IXO viewing requirement and ensures that the Sun does not intrude upon mirror or instrument





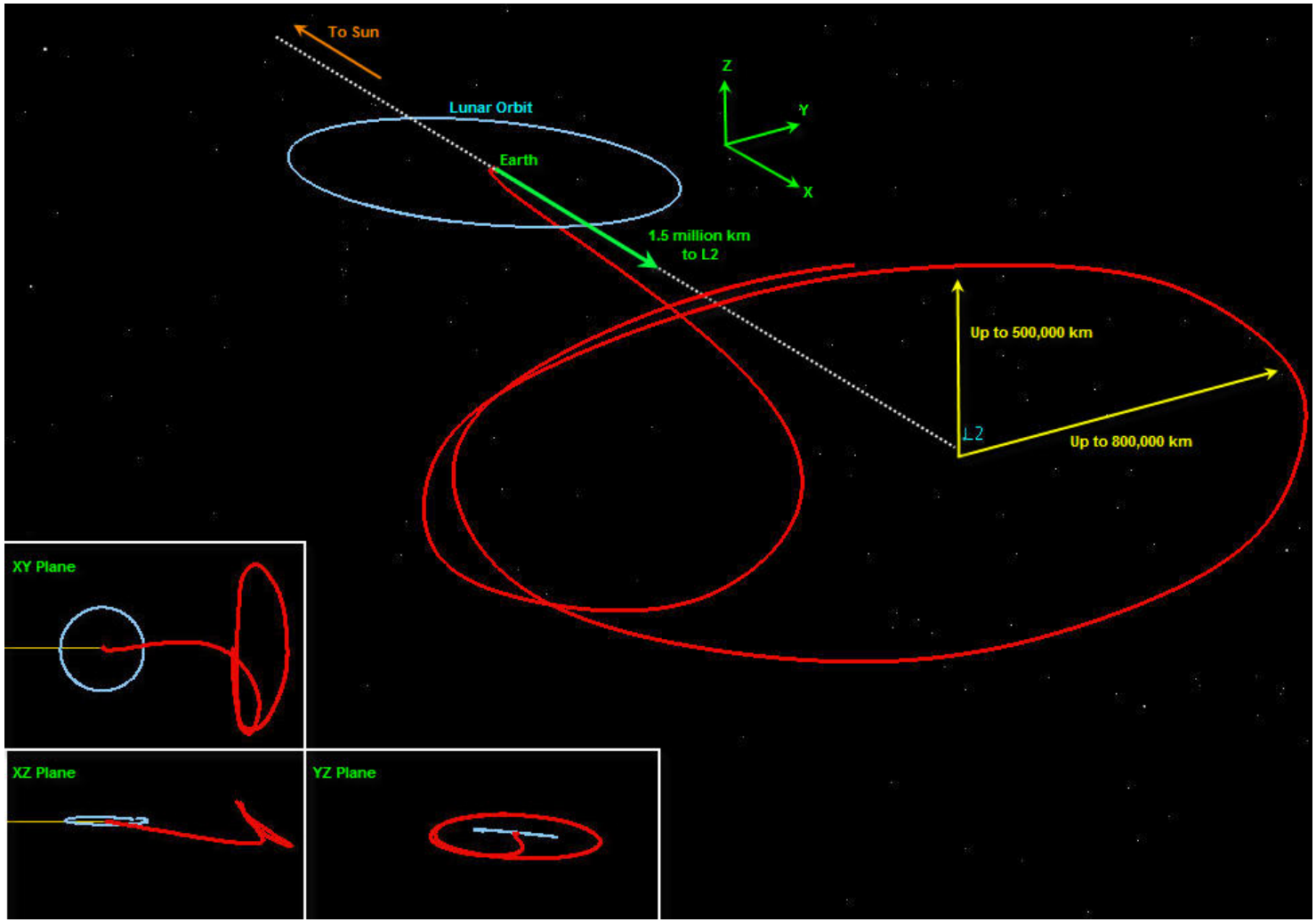
L2 Orbit Possibilities

- There are three distinct orbit types possible (depending on launch parameters)
  - **Halo:** Periodic orbit, in-plane frequency matches out-of-plane frequency (e.g. SoHO)
  - **Lissajous:** Quasi-periodic orbit, path will evolve through the ecliptic plane (e.g. WMAP)
  - **Toroidal:** Quasi-periodic, bounded Lissajous orbit
- Lissajous orbit are most likely to violate the IXO shadow constraint



IXO Orbit Picture

- The picture below shows IXO during the transfer to L2 as well as a single orbit about the Sun-Earth L2 point. The orbit period around L2 is roughly 6 months.



Launch Vehicle – Atlas V

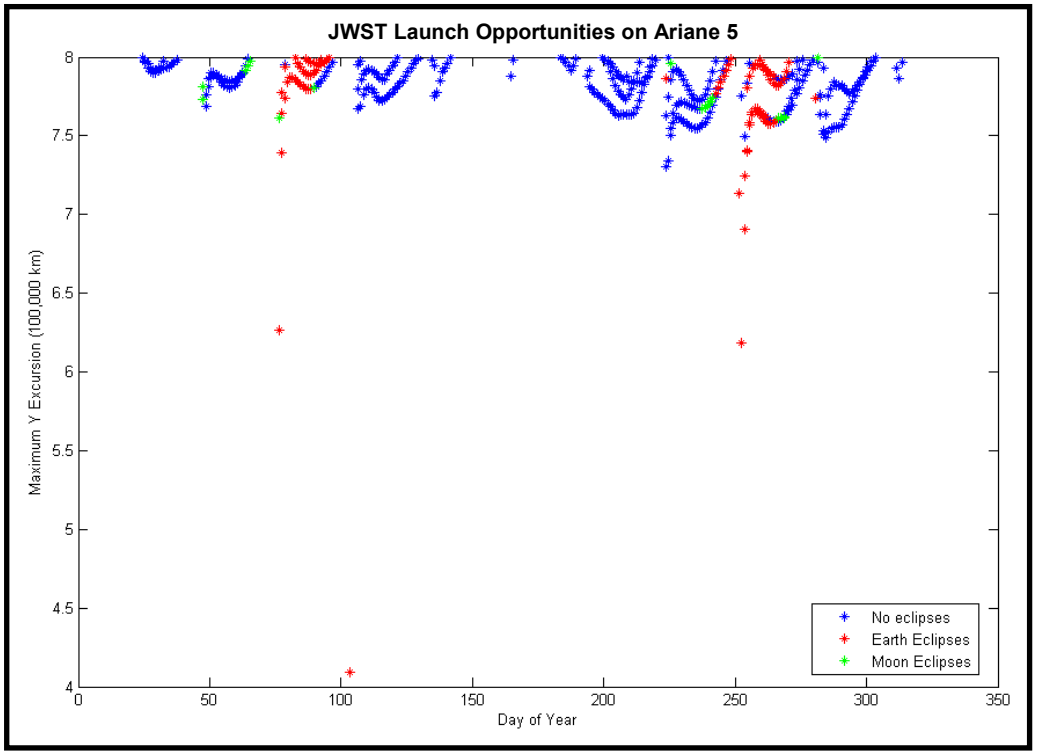
- The Atlas V flight profile establishes a parking orbit with the first burn of the Centaur upper stage
- The time from launch to the parking orbit is roughly 14 minutes
- Historically, the time spent in the parking orbit prior to the second Centaur burn (i.e. transfer trajectory insertion) ranges from 10 to 90 minutes
- Battery sizing to handle launch day power loads could restrict the ability to take advantage of the Atlas-V coast capability
  - This could reduce the launch opportunities over a 1-year window that meet the L2 orbit requirements (e.g. Y-amplitude and shadow restrictions)

Launch Vehicle – Ariane 5

- The Ariane 5 flight profile is a direct ascent from launch until injection into the transfer orbit
  - There is no parking orbit
- The time from launch to injection is roughly 25 minutes
- Flight Dynamics engineers have analyzed the Ariane 5 trajectory and its effects on the launch window in support of JWST

IXO Launch Opportunities

- The number of launch opportunities per year (that meet orbit and eclipse requirements) is a function of the candidate launch vehicle
- Ariane 5
  - Extensive work has been performed in support of JWST
  - The JWST analysis shows roughly 144 days per year that meet the L2 orbit size restrictions while exhibiting zero eclipses during operations (pic below)
- Atlas-V
  - Variable coast option yields more launch opportunities
  - Further analysis is needed to quantify this increase relative to the Ariane 5
  - Restricting the parking orbit coast time due to battery discharge during launch operations could reduce the Atlas-V launch opportunities to the same as for the Ariane 5

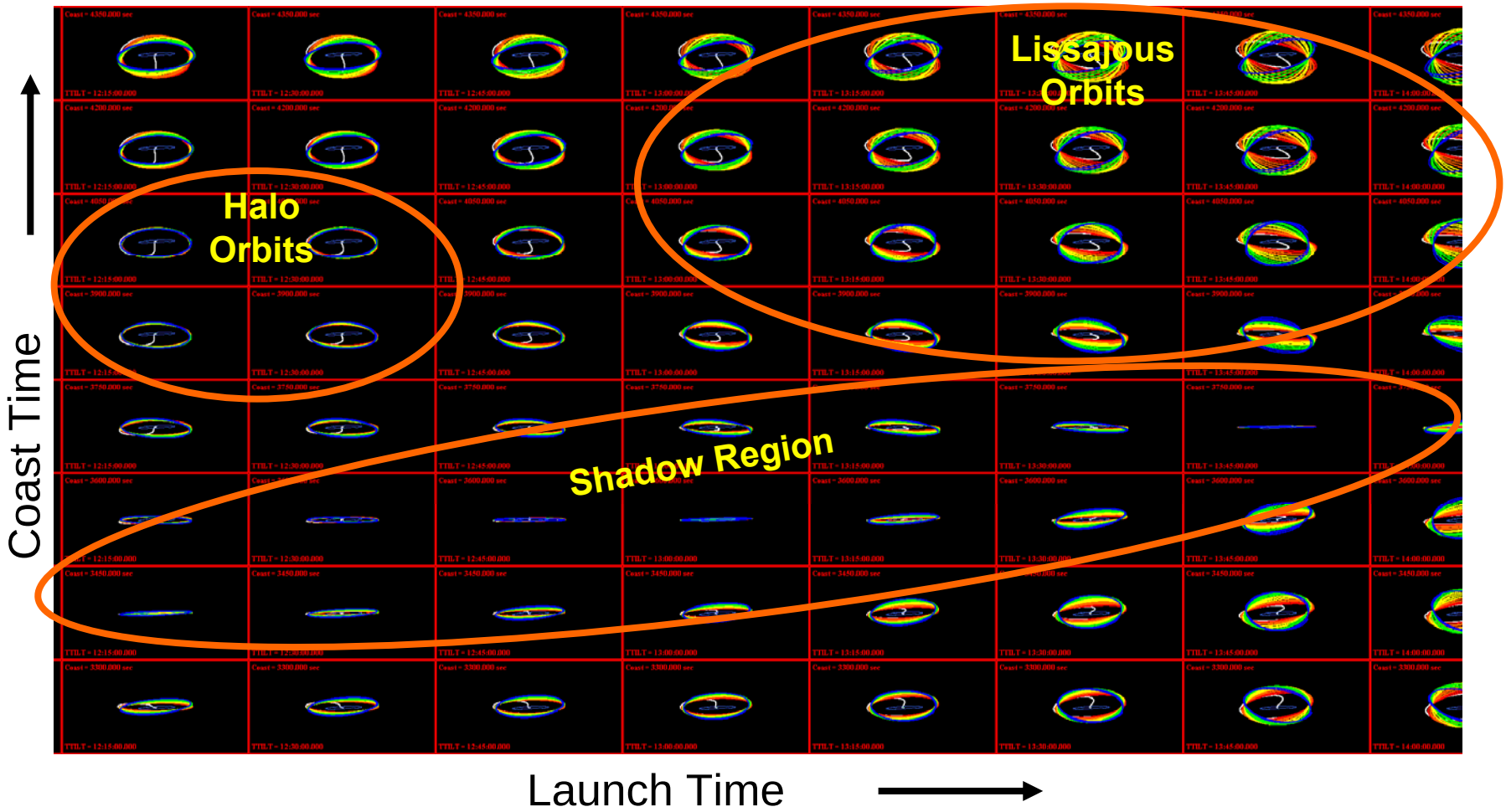


Automated Launch Window Design

- An automated script to map out the L2 orbit solution space for IXO is in process
- The available input launch parameters are
  - Launch Day (Atlas-V and Ariane 5)
  - Launch Time (Atlas-V and Ariane 5)
  - Coast Time (Atlas-V only)
- A mapping of the L2 orbit solution space helps to find the orbit with a Y-amplitude that meets mission constraints
- Further constraint evaluation can filter out cases where shadows occur

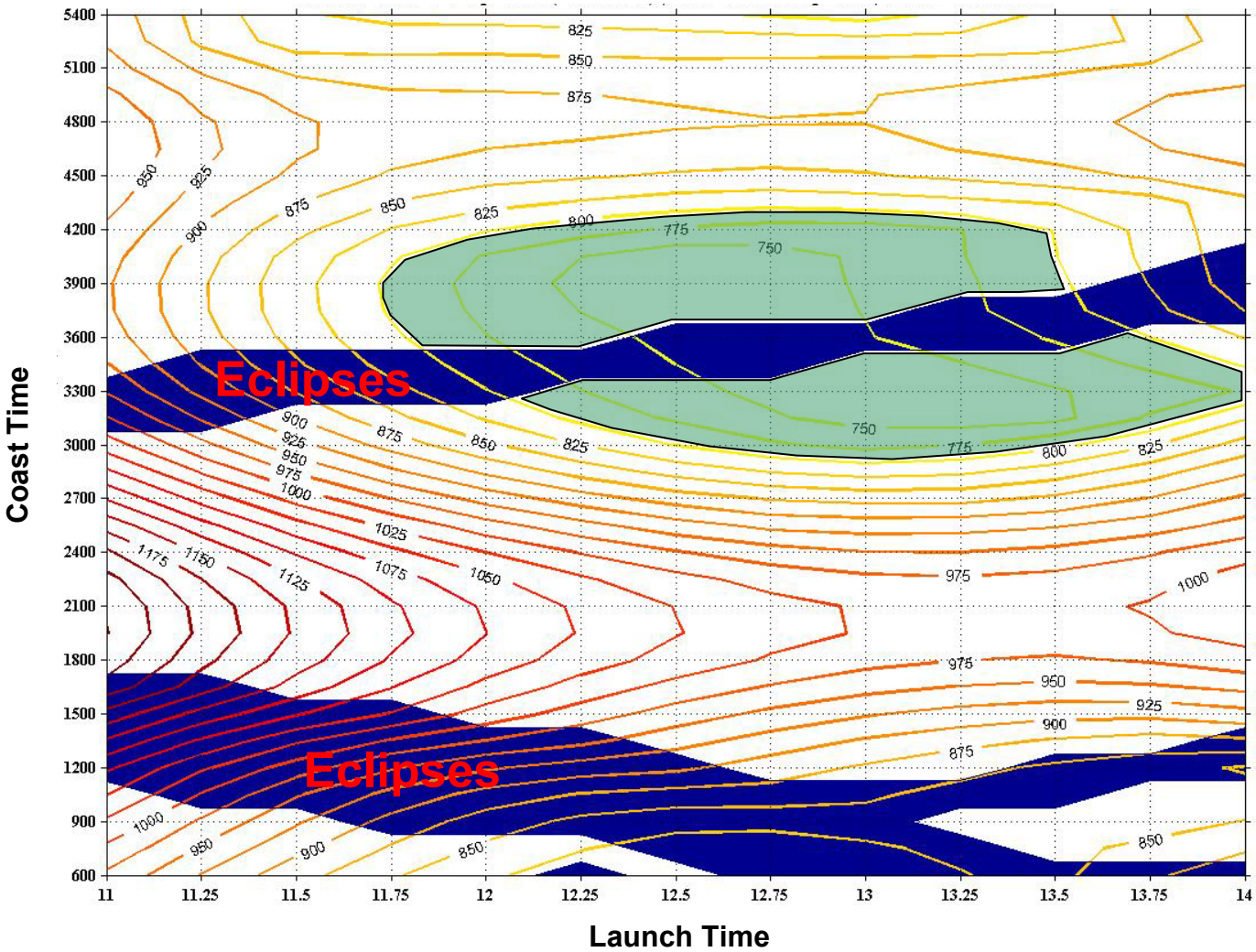
Sample L2 Solution Space

- Sample daily data (for Atlas-V) showing variation in L2 orbits YZ-plane based on changing launch time and parking orbit coast time
- For comparison, the use of the Ariane V limits us to a single horizontal slice through this solution space



Sample L2 Constraint Analysis

- Sample Y-Amplitude contour plot as function of launch and coast times (Atlas-V)
- Regions where eclipses occur are shaded in blue
- Y-Amplitude varies between 735,000 km and 1,250,000 km
- Corresponding Z-Amplitude varies between 17,000 km and 1,070,000 km
- Regions where IXO orbit constraints are satisfied are shaded in green
- Limiting coast time due to battery discharge could remove this day from launch window



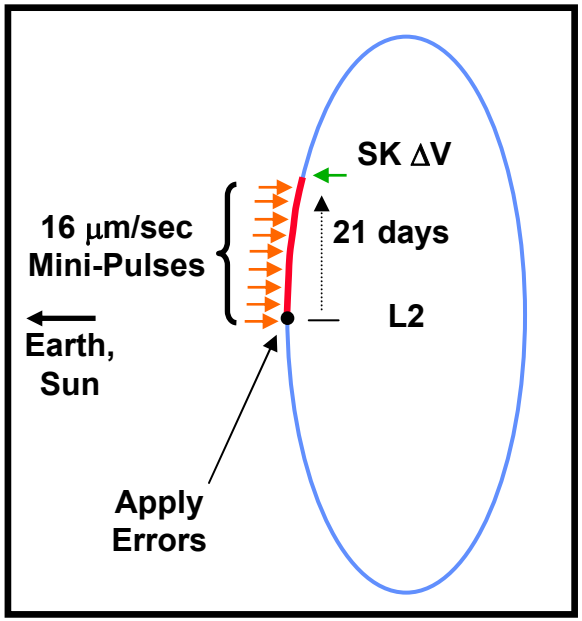
Libration Point Orbit Control

- IXO will be required to perform periodic stationkeeping maneuvers given that any orbit about the Sun-Earth L2 point is unstable due to a buildup of orbit perturbations, the chief of which is solar radiation pressure
- IXO will experience large solar torques due to a large offset between its Center of Pressure (Cp) and Center of Gravity (Cg)
- The solar torque can be countered in two ways
  - Reaction wheels store the accumulated momentum followed by dumping that momentum via thruster firings. Wheel sizing will determine the amount of momentum storage and the frequency of the off-loading.
    - WMAP unloads momentum roughly every 90 days
    - JWST plans to unloads momentum roughly every 3 days
  - Thrusters can be used to continually counter the solar torque
- The current IXO baseline has a thruster firing a mini-pulse every 18 minutes to counter the solar torque (a pure couple to eliminate translational ΔV is difficult to implement in the current observatory design)
- The characteristics of this Mini-Pulse are
  - Thrust: 0.9 N
  - Isp: 220 sec
  - Thrust Time: 0.11 sec
  - Delta-V: 16 micro-meter/s (assuming a 6300 kg spacecraft)
- This continuous Mini-Pulse will affect the stationkeeping in the mission orbit
  - The effect of the Mini-Pulsing is secondary in the transfer orbit

IXO Stationkeeping Analysis

- Because of the frequent Mini-Pulses, IXO will require stationkeeping every 21 days to maintain its orbit around L2
- Stationkeeping analysis assumes certain errors are applied at the beginning of a cycle
  - Orbit Determination (Velocity): 2 cm/s
  - Maneuver Execution: 6 mm/s (5%)
  - Solar Radiation Pressure: 10%
- Applying the errors and accounting for the Mini-Pulses leads to stationkeeping maneuver sizes of about 13 cm/s every 21 days (2.3 m/s per year)
- While this adds up to less than the budgeted 4 m/s per year we are not prepared at this time to reduce that line item at this early stage in the program

L2 Stationkeeping



IXO ΔV Budget: Atlas-V

- The Atlas-V ΔV budget for IXO
  - Launch Window 10 m/s(1)
  - ELV Dispersion Correction 20 m/s(2)
  - Mid-Course Corrections (2) 10 m/s(3)
  - L2 Stationkeeping (10 years) 40 m/s(4)
  - End of Life Disposal 1 m/s(5)
  - Total 81 m/s
- Assumptions

1) Accounts for 30 minute finite daily launch window
2) ELV Dispersion correction assumes Atlas-V dispersions corrected at TTI + 24 hours
   - Atlas-V ELV Dispersion: C3 ±0.05 km^2/s^2 (3σ) [equates to ≈ ±3 m/s at TTI]
   - Accommodates a neutral "mid"-biased launch
   - Dispersion values were obtained from KSC ELV analysts
3) Two MCC maneuvers to correct for execution errors (5%) on ELV correction maneuver
4) Budgeting 4 m/s/year
5) Small maneuver to ensure that observatory leaves the Earth-Moon system

IXO ΔV Budget: Ariane 5

- The Ariane 5 ΔV budget for IXO
  - Launch Window 5 m/s(1)
  - ELV Dispersion Correction 21 m/s(2)
  - Launch Margin 8 m/s(3)
  - Mid-Course Corrections (2) 13 m/s(4)
  - L2 Stationkeeping (10 years) 40 m/s(5)
  - End of Life Disposal 1 m/s(6)
  - Total 88 m/s
- Assumptions
  1) Deterministic maneuver accounts for Ariane performance
  2) Assumes dispersions corrected at TTI + 12 hours [consistent with JWST and Hershel/Planck]
  3) Margin to correct for dispersions at TTI + 18 hours
  4) Two MCC maneuvers to correct for execution errors (5%) on ELV correction maneuver
  5) Budgeting 4 m/s/year
  6) Small maneuver to ensure that observatory leaves the Earth-Moon system

IXO Orbit Determination

- Orbit Determination (OD) for current Libration point missions (WIND, SoHO, ACE, WMAP) utilizes batch processing
  - Batch processing performs best at L2 in the absence of orbit perturbations (e.g. ΔH maneuvers)
- Frequent ΔH maneuvers seen for JWST has led them to adopt a sequential OD process (i.e. Kalman Filter)
- The sequential OD process does a better job of absorbing the disturbances to the orbit
- JWST requirements are
  - All ΔH maneuvers provide translation (no perfect couples)
  - ΔH maneuvers (< 9 mm/s) occur every 3 days
  - Stationkeeping maneuvers every 22 days
- IXO decision to employ the Mini-Pulses (16 micro-meter/sec) every 18 minutes to control solar torque forces a similar sequential OD (with Kalman Filter) approach
- Tracking requirements assume 30 minutes of 34m DSN range and doppler data per day (alternating between North & South hemisphere stations)

Timing Requirement

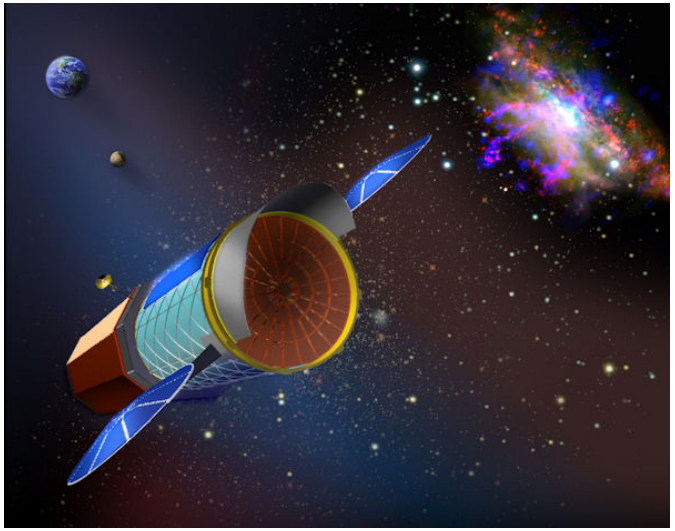
- The 100 μsec timing requirement presented during the January, 2009 MDL study would relate to a 30 km position accuracy but only a fraction of this will be allocated to orbit determination
  - The timing requirement is tight and a driver if the 100 μsec is a 3σ number
- A detailed budget of the timing requirement and the portion allocated to orbit determination is on the following page
- The current budget allocates 28 μsec for orbit determination and this equates to 8.4 km position knowledge
- JWST position requirement is 50 km
- While it is believed that the filter can do better than 50 km it is unclear at this time if we can meet the 8.4 km requirement
- Further analysis will be required to verify if this number can be met

Future Work

- Quantify the change in launch opportunities going from an Ariane 5 (like JWST) to an Atlas-V
  - Work is needed in the area of automated trajectory generation for the Atlas-V (refine current scripts)
  - We need to modify the current Atlas-V scripts to develop an automated trajectory generation tool for the Ariane 5 case
- Need to verify the orbit determination architecture given the constant mini-pulses will continually perturb the orbit
- Additional work is needed to determine if the orbit determination position requirement of 8.4 km can be met using a sequential OD process and incorporating IXO's Mini-Pulsing strategy

IXO Table Top Review

2009 03 12
NASA GSFC, Bldg 23, Room C130D



Pointing

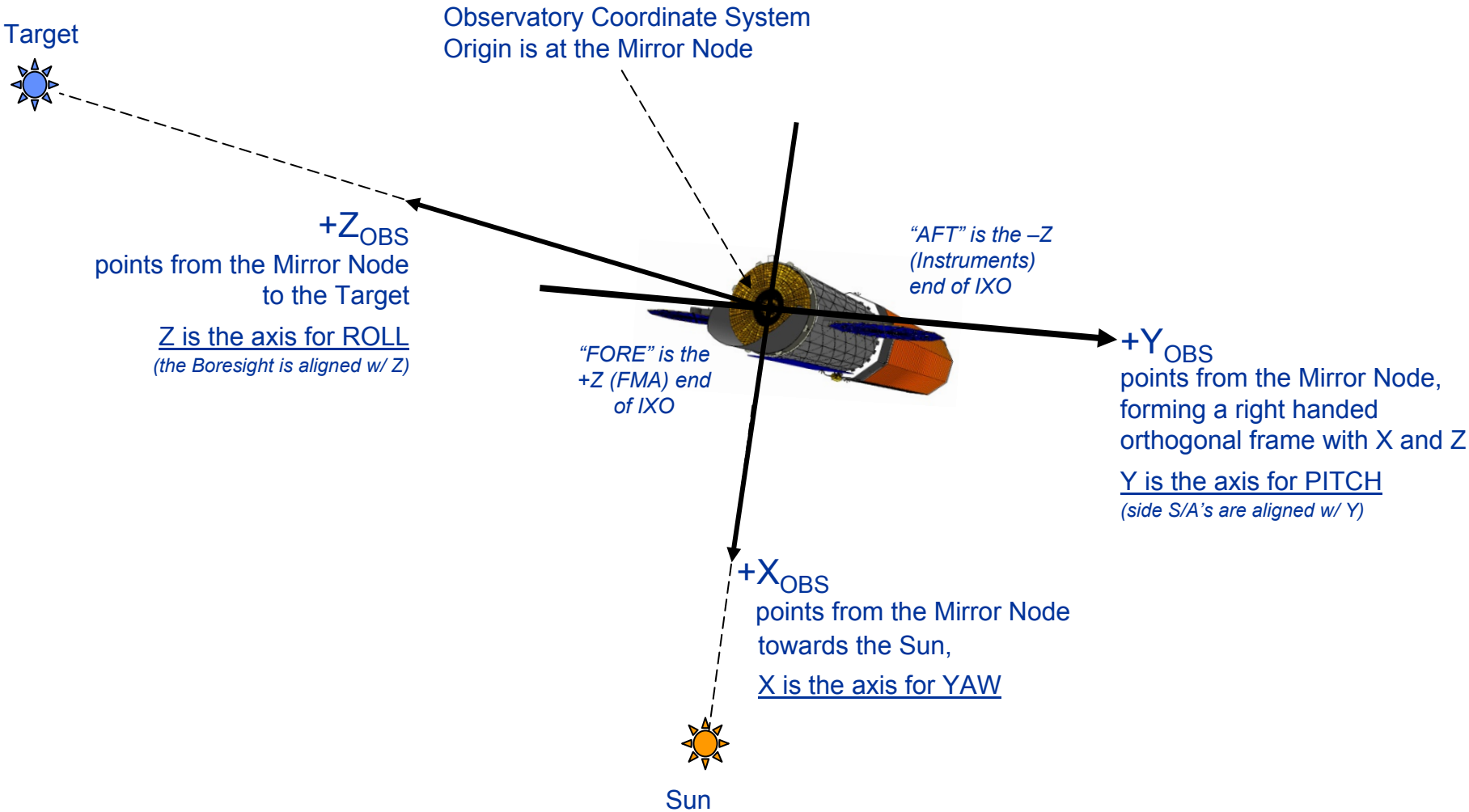
Gabe Karpati
IXO Mission Systems Engineer

OUTLINE

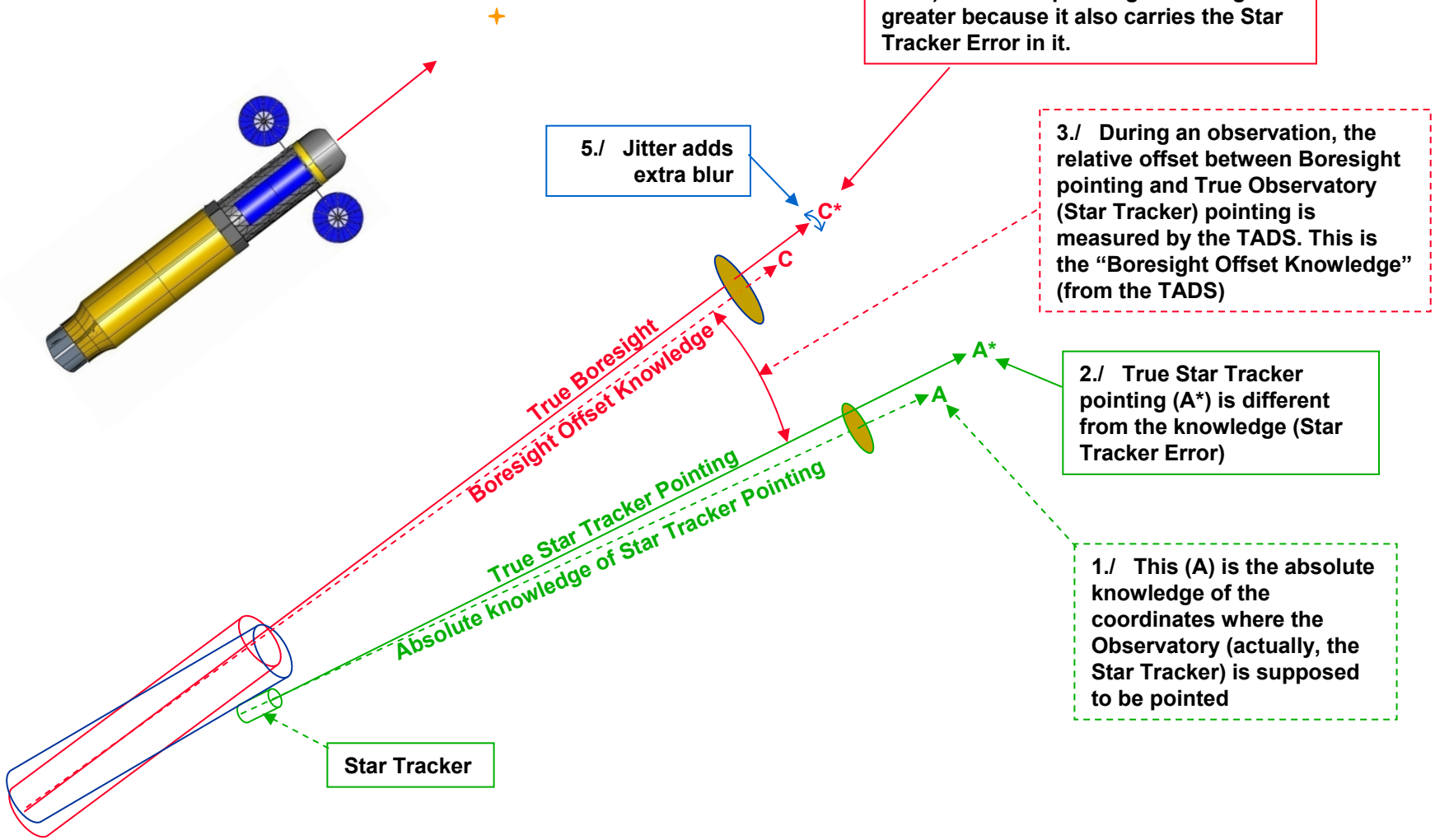
- Pointing Basics
- ACS Overview
- Requirements Flowdown, Basis of Calculations
- Error Budgets
- Control System Performance

Pointing Basics

Observatory Coordinate System



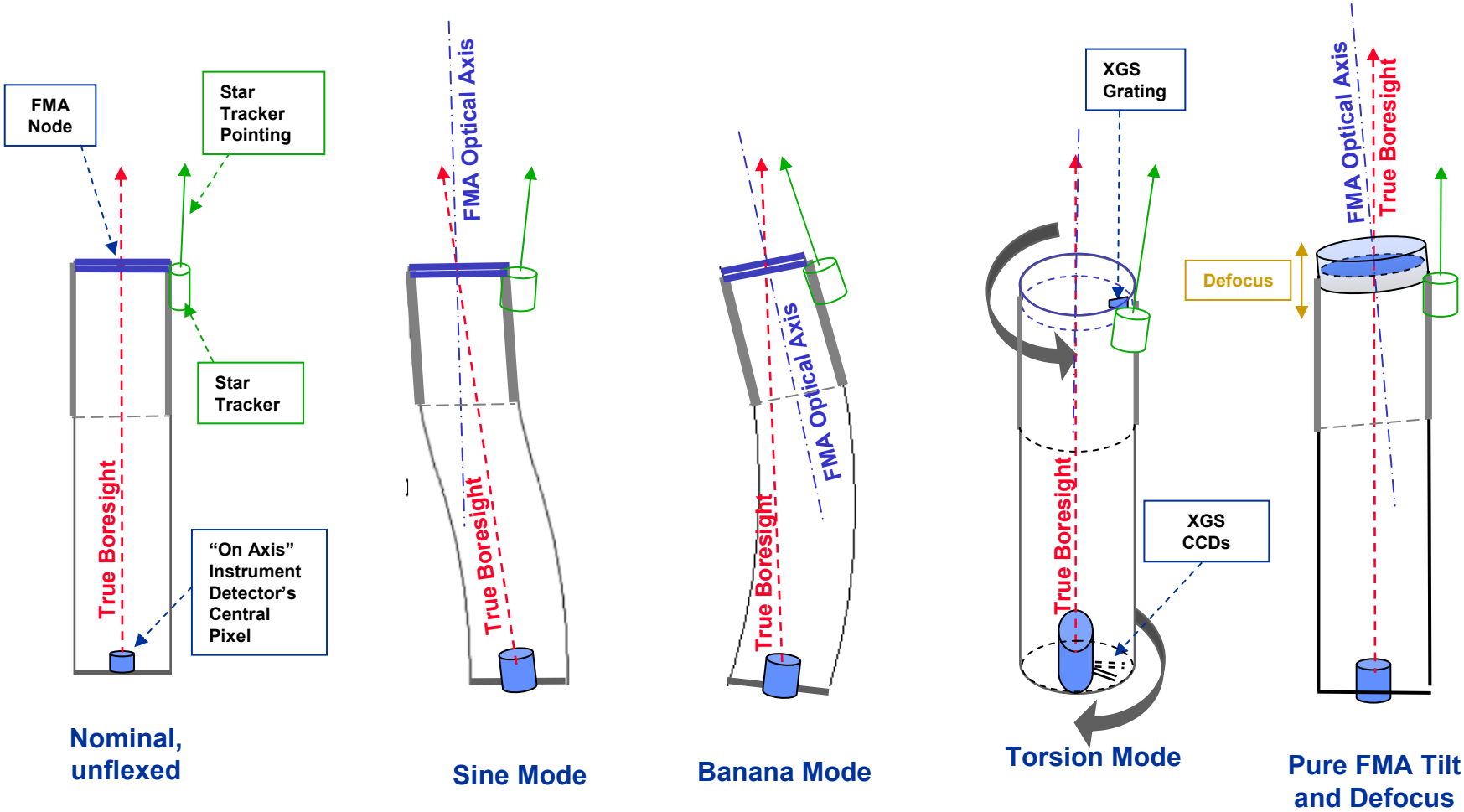
Observatory Level Pointing Basics



True Boresight is defined as the line connecting the "Center Pixel" on the XMS/WFI to the FMA node.

Flex Body Effects and Structural Misalignments

Boresight to Star Tracker and Boresight to FMA Optical Axis Misalignments



Observatory Level Pointing Performance Summary

Term	Definition	Requirement	Predicted Performance	Stat
Image Position Reconstruction Knowledge (a.k.a.: "Aspect Reconstruction)	The absolute knowledge of an image's position relative to the Truth:	• Radial: 1 arcsec (that is Pitch and Yaw combined, equivalent to ~0.7" pitch and ~0.7" roll) • Roll: 3 arcsec	• Radial: .54 arcsec • Roll: 2 arcsec (stability over a science observation)	HPD
Image Position Control	The absolute precision of placing and keeping an image on the Focal Plane Detector	• Pitch and Yaw: 10 arcsec • Roll: 30 arcsec	▪ Pitch and Yaw: 1.54 arcsec • Roll: < 10 arcsec	3σ
Defocus	Abs. max. FMA Node to Detector distance variation without correction by any focus mechanism	• +/- 0.3 mm	▪ +/- 0.16 mm	3σ
Lateral Translations	Boresight Misalignments Relative to FMA Optical Axis due to Metering Structure translations	▪ +/- 1.6 mm (16 arcmin)	▪ +/- 1.2 mm (12 arcmin)	3σ
Jitter (excluded from the Image Position Knowledge requirements)	Jitter effects encompass all high frequency errors above the bandwidth of the Control System and Monitoring System	▪ 200 milliarcsec over 200 msec	▪ 20 milliarcsec abs. worst case over any period msec By Reaction Wheel momentum management in a 5 RW configuration, a steady state jitter of .2 milliarcsec is achievable	HPD

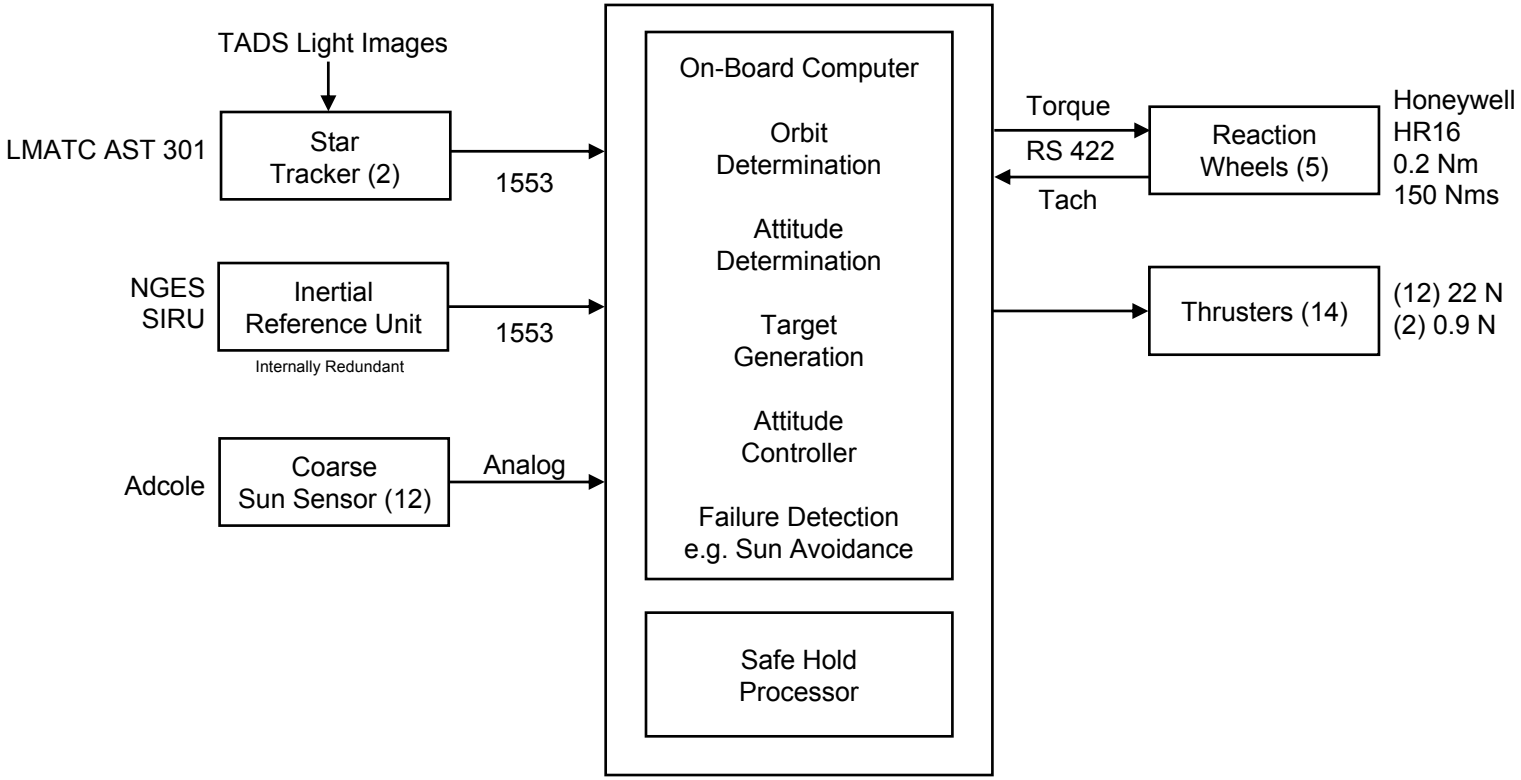
Note: one mm corresponds to ~10" (or 1 " to 100 um) at 20m

ACS Overview: Sensors and Actuators

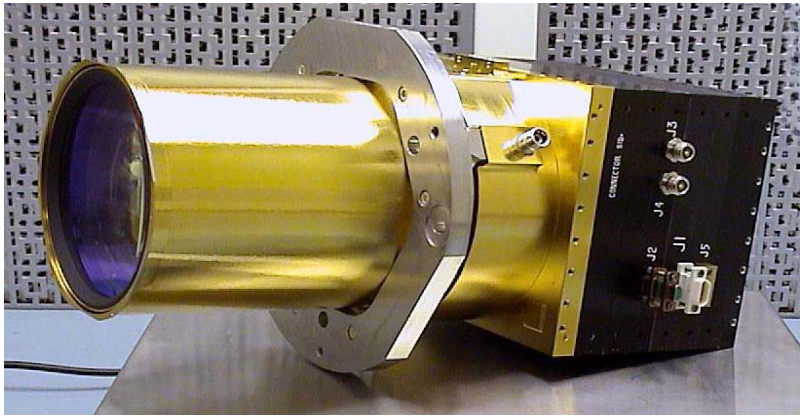
ACS Overview

- Three-axis stabilized, inertial pointing
  - X axis points to Sun, Z axis points to science target
  - Solar panels pointing towards sun maintained for all modes: Science, slew, maneuver, safe hold, and cruise
- Two AST 301 Star Trackers
  - Coaligned with telescope boresight to provide precision attitude knowledge
  - Also used as part of the Telescope Aspect Detection System (TADS)
- IRU mounted on S/C Bus
  - Internally redundant
- Five reaction wheels arranged in a JWST-like "L-infinite configuration to maximize momentum, biased for a 4:1 or greater ratio between the X/Y axis and the Z axis
  - RWL Torque Capability per Axis: 0.2 Nm (conservative)
  - Slews require authority mainly in the X axis
  - Momentum accumulation primarily in the Y axis
- Nearly continuous low disturbance thruster based solar torque unloading allows uninterrupted science observations
- Mass Properties
  - Ixx = 320,000 kgm^2
  - Iyy = 320,000 kgm^2
  - Izz = 12,000 kgm^2
- Digital Control (PID) with 0.02 Hz Bandwidth
  - Uses Star Tracker Exclusively (gets better with Gyro, e.g. SIRU)

ACS Block Diagram



Spitzer's AST-301 Star Tracker (by LMATC)



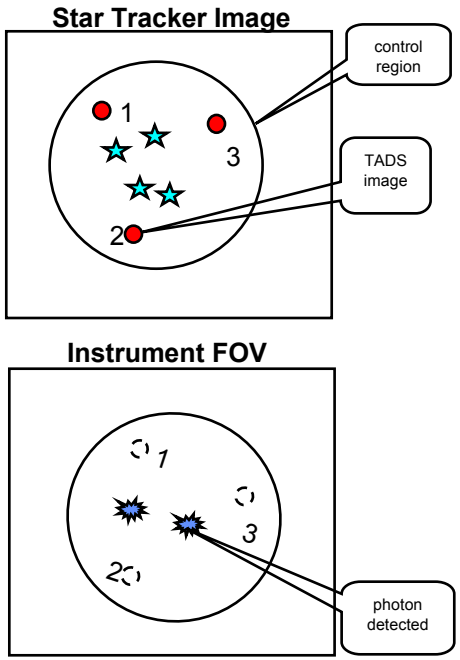
- Accuracy
  - 0.2 as (1σ), X and Y axes*
    - * *before in flight optical distortion calibrations*
  - 6.0 as (1σ), Z axis
- Detector / FOV
  - FOV is 5-by-5 degree
  - Clearance 3.54 degree ½ cone angle
  - 512 x 512 pixels
  - Pixel size: 15 x 15 micrometer = 35 x 35 as
- NEA
  - 0.11 arcsec about X and Y axes, 3.1 arcsec about Z axis
  - Bias error is 0.15 about X and Y axes, 4.0 arcsec about Z axis (1 sigma)
  - Centroiding to 1/100 of a pixel
- Senses 9.2 magnitude start (~50 stars)
  - Responds to 450-850 nm
- Guide Star Compensation for
  - Proper motion
  - Parallax
  - Velocity aberration and optical distortion
- Output quaternion at 2 Hz rate, Operable (at reduced accuracy) at up to 2.1 deg/s
- Acquisition time: 3 seconds
- Mass: 7.1 kg per unit; Power: 18 W per unit; Dimensions: 30.2 cm (L) x 13.3 cm (H) x 15.3 cm (W)
- 1553 bus
- Heritage: Spitzer

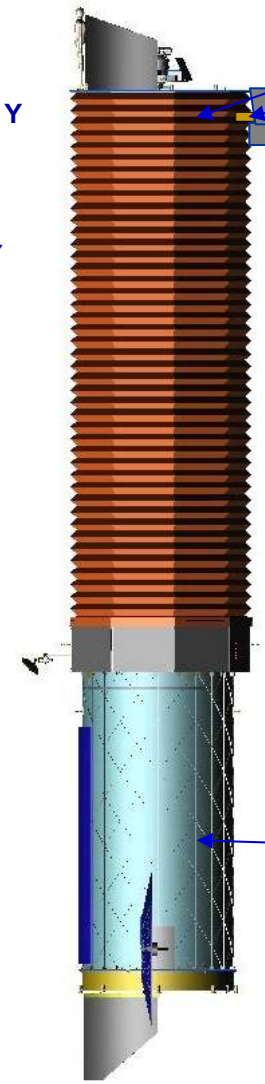
Source: **SIRTF Autonomous Star Tracker (SPIE Paper 4850-12), Roel van Bezooijen**

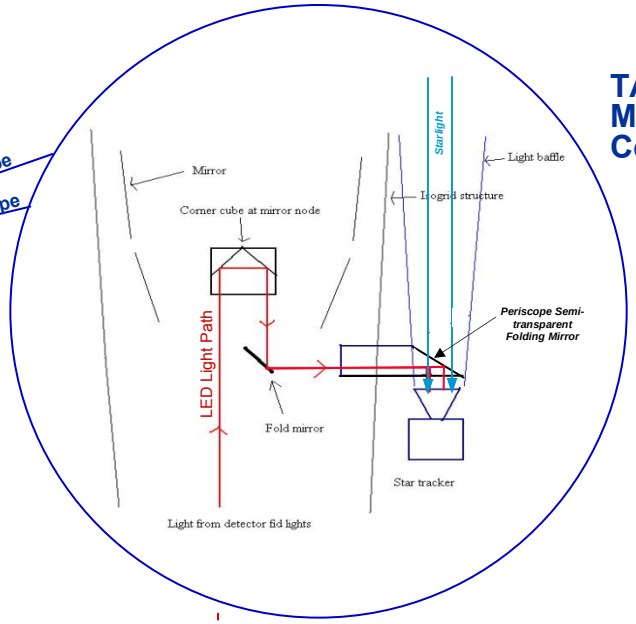
Telescope Aspect Determination System (TADS)

TADS Parameters

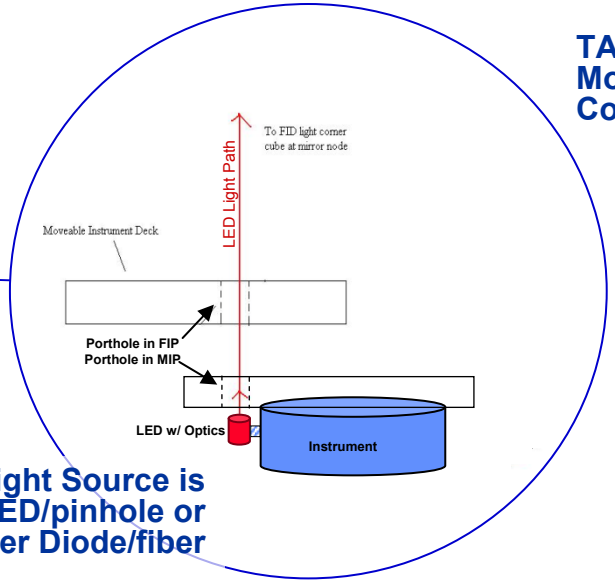
- **Accuracy Requirements:**
  - 0.8 arcsec (HPD) (.08 mm) in X and Y
  - 10 arcsec (HPD) (.08 mm) in in Torsion
- **Expected Performance:**
  - 0.11 arcsec.011 mm (3σ) in X and Y
- **Dynamic Range:**
  - +/- 100 arcsec (10 mm) in X and Y
  - +/- 20 arcmin (~10 mm) in Torsion







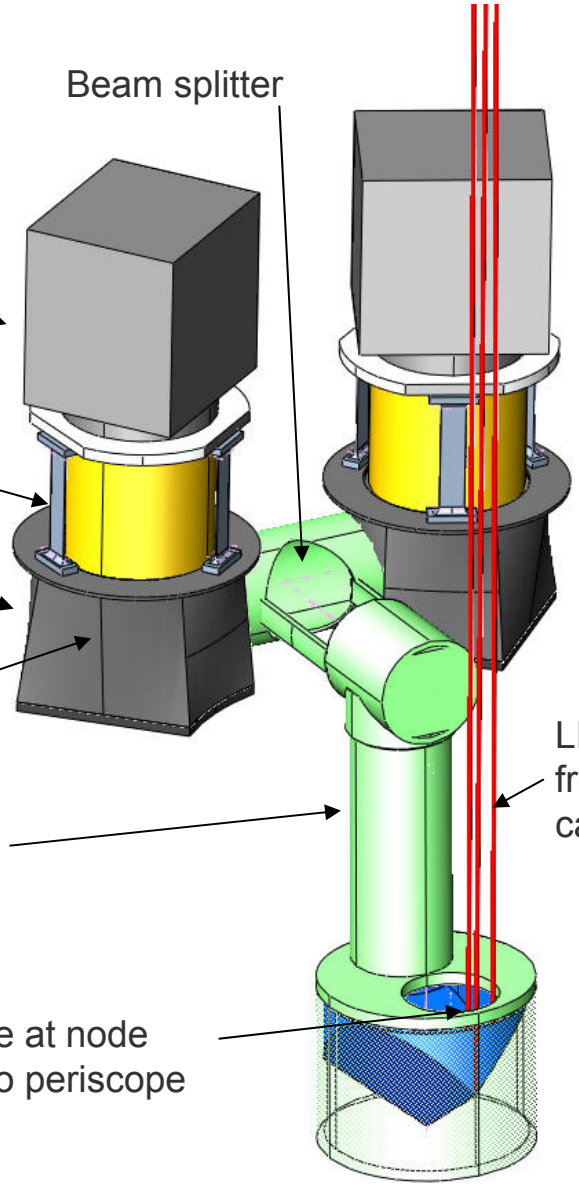
TADS Optics Module Components

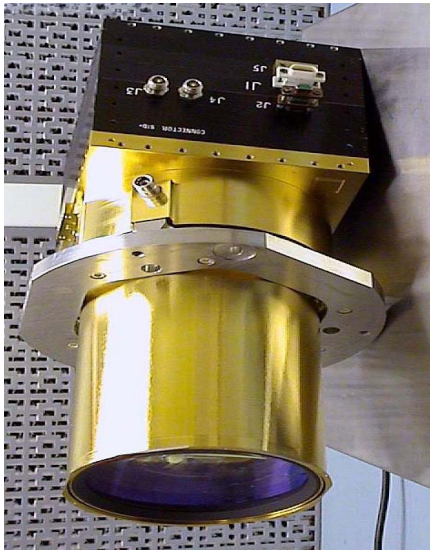


TADS Instrument Module Components

Light Source is LED/pinhole or Laser Diode/fiber

TADS Components



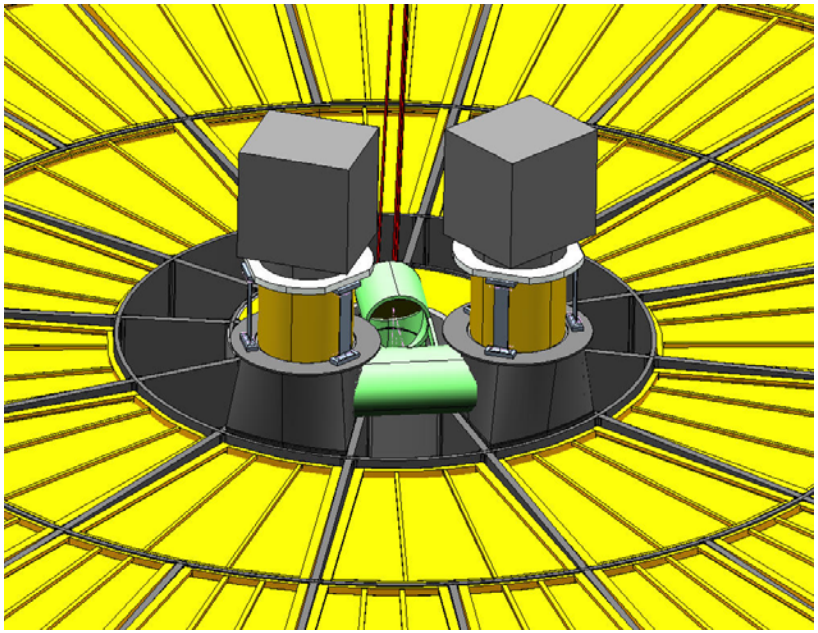


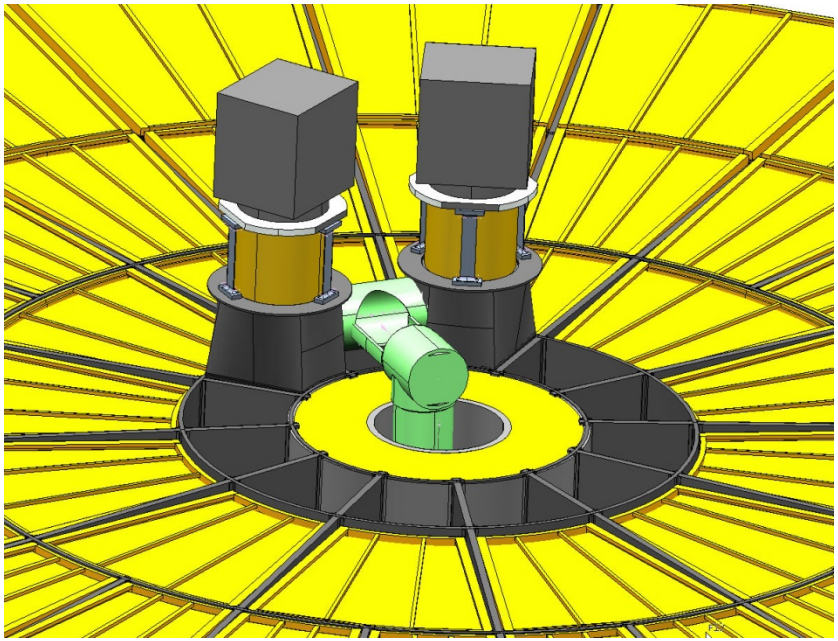
AST-301 Tracker

FID Light (LED light) assembly, 45mm long

TADS

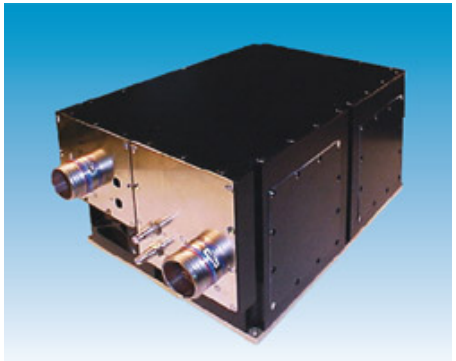
- A lightweight stand elevates the tracker lens assembly about 12 cm above the FMA.
- The periscope tube enters the stand where a fold mirror is located to turn the beam up and into the tracker FOV.
- Tracker mounts to 3 blade flexures via its Invar mounting flange.
- Flexures mount to top of the stand.





Adcole Coarse Sun Sensor and SIRU

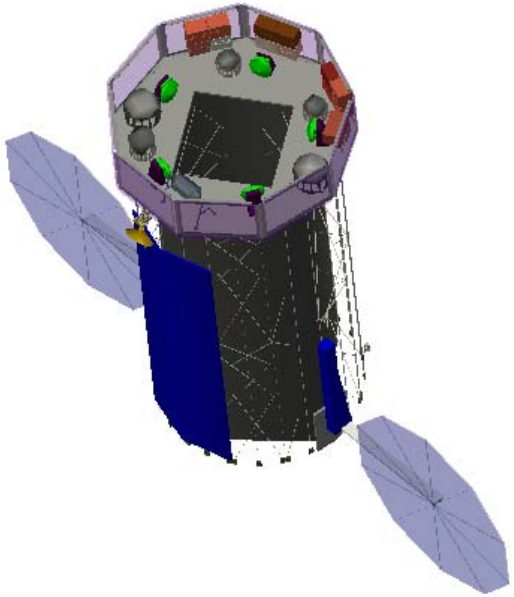
- Individual CSS detectors provide 2π steradian coverage
- 12 detectors distributed across the observatory provide redundant full 4π steradian coverage



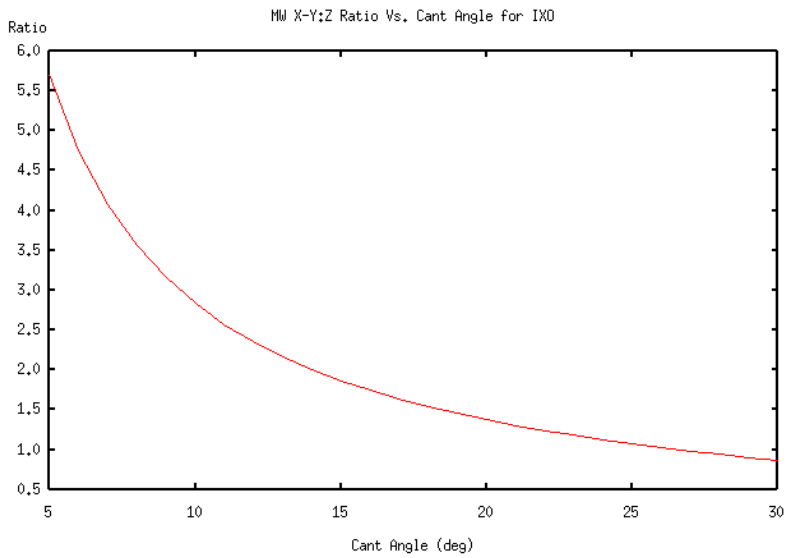
- Manufacture NGES
- Technology HRG 3 axis
- Gyro Performance
  - Angle Random Walk 0.00015 deg/rt-hr
  - Angle White Noise 0.003 arcsec/rt-Hz
- Range 12 deg/sec
- Units Required 1 (internally redundant)
- Data Interface RS-422/1553
- Mass 4.5 kg
- Power 38 W
- Size 18 x 15 x 29 cm
- Cost $1500k

Reaction Wheel: Honeywell HR 16-150

- Momentum Storage
  - 150 NMS
- Reaction Torque
  - 0.2 Nm
- RS 422 I/F
- Mass: 15 kg per unit
  - HR(16) series rated at TRL-7
  - 150 Nms version not widely flown

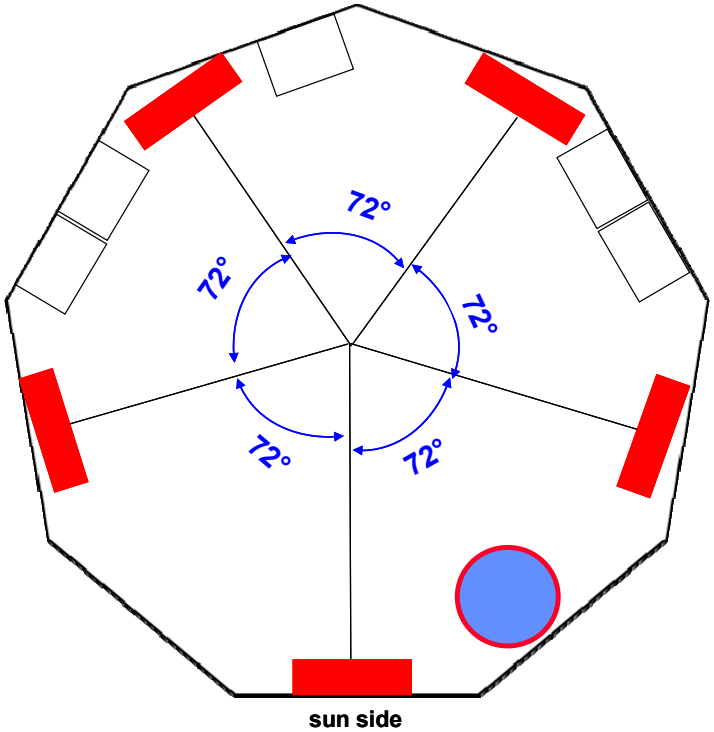


Proposed Reaction Wheel Orientation



Cant angle selected based on desired X-Y:Z ratio
A 4:1 ratio results in ~ 7 deg cant angle

Reaction wheels canted slightly up out of page



Reaction Wheel Configuration Slew Capability

- Calculated for five Honeywell HR16 wheels
  - In pyramid configuration (like Spitzer)
  - Pyramid apex in Z direction
  - <10 deg cant angle (can be optimized depending on yaw (± 180 deg) versus roll (± 20) slew requirements)
- Each wheel
  - Angular momentum capability: 150 Nms
  - Torque capability: 0.2 Nm (is function of speed)
- Slew speed
  - 60 deg yaw: 0.52 hrs (margin not included)
  - 20 deg pitch: 0.41 hrs (margin not included)

Requirements Flowdown, Basis of Calculations

Pointing Requirements Flowdown from XMS Instrument Image Quality Error Budget

P. B. Reid
Harvard-Smithsonian Center for Astrophysics
May 27, 2008

Micro-calorimeter Spatial Resolution Goals Error Budget - Mission(1 SXT, single Atlas V Launch)

	ITEM (HPD - arcsec)	RQMT	Margin		Allocation						RATIONALE
1	Calorimeter 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
4	Telescope level effects				1.51						RSS
5	Image Reconstruction errors (over obs)					1.41					RSS
1 → 6	Attitude knowledge drift						1.00				Chandra experience
7	FMA/XMS focal plane drift (thermal)						1.00				Chandra experience - includes FID light system
2 → 8	FMA/XMS vibration effects					0.20					Chandra experience (jitter)
3 → 9	FMA/XMS misalignment (off-axis error)					0.05					field dependent aberration =+/- 30 arc-sec alignment
4 → 10	FMA/XMS 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				
21	Module to Module alignment						1.00				
22	Module						3.76				
23	Distort. & misalign due to module packing							0.71			
24	Mirror Pair Co-alignment							0.71			
25	Mirror Pair							3.63			RSS
26	P-S alignment in module(using CDA)								1.12		RSS
27	CDA Dynamic Accuracy									0.50	
28	CDA Static Static Accuracy									0.50	
29	Thermal Drift									0.50	
30	Focus and Coma Alignment									0.71	
31	Reflector Installation in module								1.00		
32	Reflector Pair (P-S)								3.30		Est based on tech dev program to date
	Color Code	Rqmt		Margin		RSS Predict			Allocation		

Derived key Observatory Pointing Requirements

1. **Attitude Knowledge:** 1.0 as [HPD]
2. **Jitter:** +/- 0 2 arcsec = +/- 0.02 mm in X and Y
3. **Max. X/Y displacement** (for Imaging only!) : +/- 30 arcsec = +/- 3 mm in X and Y
4. **Defocus:** +/- 0.5 arcsec => +/- 0.3 mm in Z (assuming a conservative f(6) beam)

Note: at 20m focal length 10 as =~ 1 mm

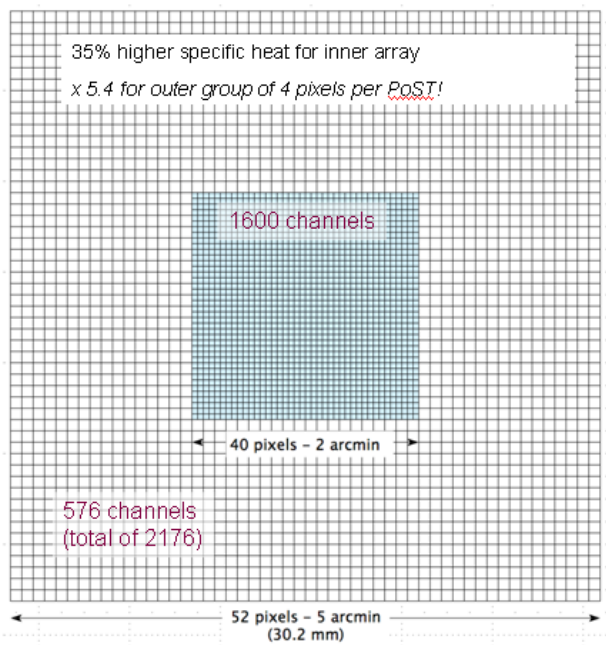
Considerations for Image Placement

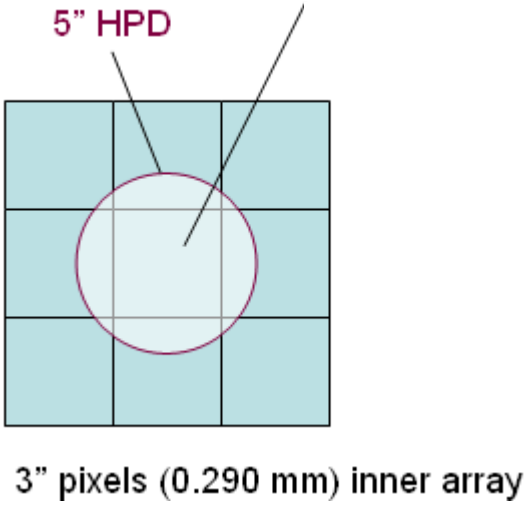
(Pointing Control Errors and Metering Structure Twist Effects; Static and Dynamic displacements combined)

Top Requirement: keep images on their appropriate Detectors at their nominal position to within the allowable number of pixels

1. **XMS, WFI, HXI**
   - Image displacements due to Pointing Errors follow straight "thin lens" geometry
   - Image displacements due to Metering Structure Torsion: no first order effect
2. **XGS w/ CAT Gratings**
   - Factors that contribute to image displacements (due to Pointing Errors)
     1. Pointing Errors in the CROSS DISPERSION direction cause image displacements that follow nearly straight "thin lens" geometry
     2. Pointing Errors in the DISPERSION direction cause image displacements that follow interferometric laws (which, as it turns out, is also very near conform to "thin lens" geometry)
     3. Metering Structure Torsion causes straight one-to-one image displacement
   - Note: The assessment for the XGS examines each of the above displacement contributors as an isolated effect, disregarding cross couplings. A more thorough and more realistic analysis is required to evaluate composite displacements due to all the displacement contributors acting simultaneously.

XMS
Detector and Pixel Geometry (20m Focal Length)





XMS - Image Placement Control

PROJECTION GEOMETRY

- **Projection of images on the XMS Detector conform to "thin lens" (or "pinhole optics") behavior in both X and Y. Thus, image displacement due to Observatory tilt follows straight "pinhole" geometry.**
- **A 15" diameter circle (approximately 5 pixels wide) encompasses < 95% of an 5" HPD image** ***(assuming Gaussian distribution; as only half of the energy of a "5" HPD image" is within a 5" diameter circle)***

APPROACH

- **To place and keep a suitably selected extended image on the XMS core detector pixels, *a 5 pixels wide zone* (10 pixels total) on the inside edges of the central 40x40 pixel field is designated as the *"pointing error buffer"*. To assure that image displacements don't exceed the "pointing error buffer", the following requirement is established:**

XMS REQUIREMENT:

- **The IXO Observatory shall place and keep <u>a point image</u> on the center of the XMS Detector within +/-5 pixels. This is a total requirement including all contributing effects to XMS pixel alignment.**

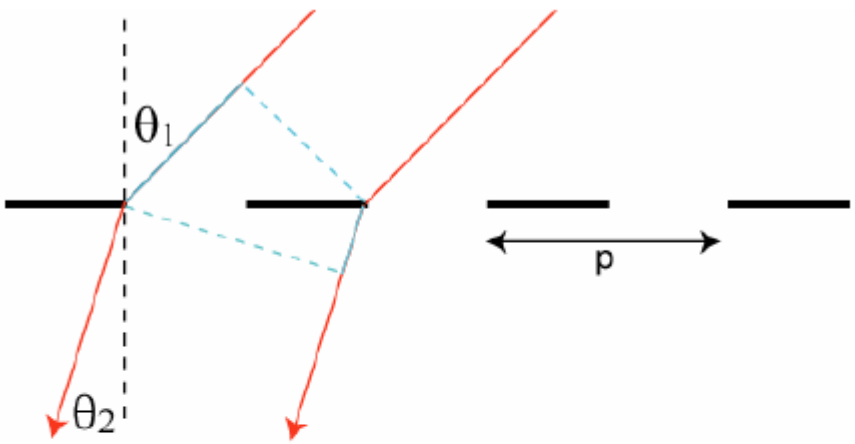
•Note: one mm corresponds to ~10" at 20m

XGS w/ CAT Grating - Cross-dispersion Direction Image Placement Control (i.e. Mispointing Normal to Rowland Circle)

- 512 pixels (7.68 mm) available for cross-dispersion direction
  - Includes 100 pixels each at top and bottom of detector for background measurements
  - Leaves 312 pixels = 4.68 mm for cross-dispersion direction of spectra
- 5 arc-sec HPD → 14.7 arc-sec 95 per cent power width (assumes Gaussian distribution) in the cross dispersion direction
- Plate scale = 0.1 mm/arc-sec
  - 95 per cent power image width → 1.47 mm
- 4.68 mm available for cross-dispersion image minus 1.47 mm image yields 3.21 mm available
- Thus, +/- 1.6 mm (3.2/2) is available for all contributors to relative CCD to spectrum alignment. This includes all the contributors in the following budget. ***This is considered a +/- 3σ tolerance.***
- *Caveat* – it may be possible to reduce the number of pixels allocated to background. This would increase the top level tolerance.

Courtesy Paul Reid 9/2008

XGS w/ CAT Grating - Dispersion Direction Image Placement Control Diffraction Gratings Basics (courtesy Ralf Heilmann)



path length difference (PLD) = p (sin θ_1 - sin θ_2)
constructive interference: PLD = mλ

Grating Equation:

$$m\lambda = p (\sin \theta_1 - \sin \theta_2)$$

XGS w/CAT – 1 keV Image displacement in the Dispersion direction

Parameters	Ref	Equation	Value	Unit	Comments
1 keV Wavelength	lambda		1.24	nm	
m (order)			7		
m-th order pathlength			8.680000	nm	
Grading Pitch	p		100.00	nm	
Incident angle	alpha	nominal pointing - 0 arcsec	3.00000	degrees	Observatory tilt (incident + blaze angle) measured in the Rowland Circle plane
PLD - Section a	a	d * sin(alpha)	5.233596	nm	
Focal Length	F		20.000	m	
5th Order Image position	x	This is the Variable	0.6895525	m	Distance from 0th order on Rowland Circle
PLD - Section b	b	p * x/(SQRT(400+x^2))	3.44572	nm	
Total PLD minus m-th order pathlength	PLD	a+b - [m-th order pathlength]	-0.0006892132	nm	Goal seek for this = 0
1 keV Wavelength	lambda		1.24	nm	
m (order)			7		
m-th order pathlength			8.680000	nm	
Grading Pitch	p		100.00	nm	
Incident angle	alpha	off pointing - 10 arcsec	3.00278	degrees	Observatory tilt (incident + blaze angle) measured in the Rowland Circle plane
PLD - Section a	a	d * sin(alpha)	5.238437	nm	
Focal Length	F		20.000	m	
5th Order Image position	x	This is the Variable	0.6887206	m	Distance from 0th order on Rowland Circle
PLD - Section b	b	p * x/(SQRT(400+x^2))	3.44156	nm	
Total PLD minus m-th order pathlength	PLD	a+b - [m-th order pathlength]	0.0000000648	nm	Goal seek for this = 0
		1 keV 7th order moved by:	0.831921 8.579802	mm arcsec	

1 keV Wavelength	lambda		1.24	nm	
m (order)			10		
m-th order pathlength			12.400000	nm	
Grading Pitch	p		100.00	nm	
Incident angle	alpha	nominal pointing - 0 arcsec	3.00000	degrees	Observatory tilt (incident + blaze angle) measured in the Rowland Circle plane
PLD - Section a	a	d * sin(alpha)	5.233596	nm	
Focal Length	F		20.000	m	
5th Order Image position	x	This is the Variable	1.4369748	m	Distance from 0th order on Rowland Circle
PLD - Section b	b	p * x/(SQRT(400+x^2))	7.16640	nm	
Total PLD minus m-th order pathlength	PLD	a+b - [m-th order pathlength]	-0.0000038848	nm	Goal seek for this = 0
1 keV Wavelength	lambda		1.24	nm	
m (order)			10		
m-th order pathlength			12.400000	nm	
Grading Pitch	p		100.00	nm	
Incident angle	alpha	off pointing - 10 arcsec	3.00278	degrees	Observatory tilt (incident + blaze angle) measured in the Rowland Circle plane
PLD - Section a	a	d * sin(alpha)	5.238437	nm	
Focal Length	F		20.000	m	
5th Order Image position	x	This is the Variable	1.4359990	m	Distance from 0th order on Rowland Circle
PLD - Section b	b	p * x/(SQRT(400+x^2))	7.16156	nm	
Total PLD minus m-th order pathlength	PLD	a+b - [m-th order pathlength]	-0.0000038921	nm	Goal seek for this = 0
		1 keV 10th order moved by:	0.975801 10.063672	mm arcsec	

XGS w/ CAT Grating

Dispersion Direction Image Placement Control, i.e. Mispointing - in the Plane of the Rowland Circle

PROJECTION GEOMETRY

- In the Dispersion direction (on the Rowland Circle), displacement of a CAT Grating's image follows interferometric laws.

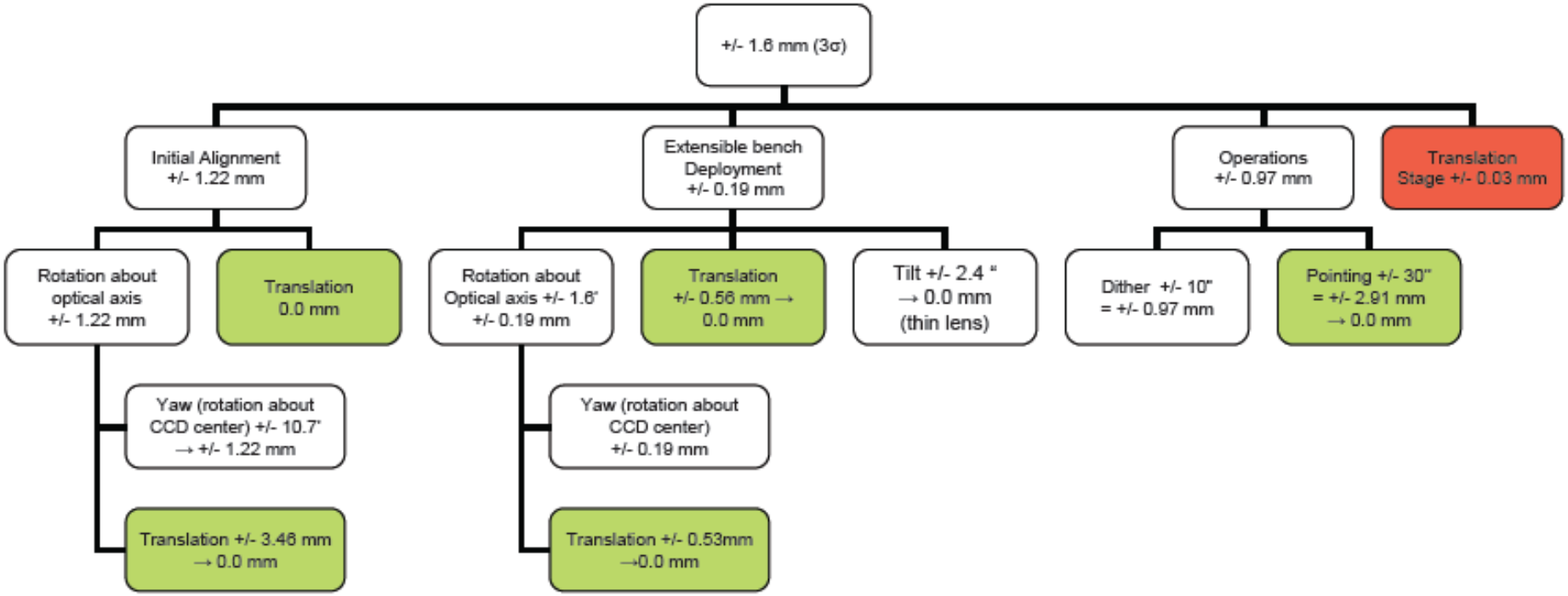
Due to 10 arcsec off pointing:		
1 keV 7th order moved by:	0.832	mm
	8.580	arcsec
1 keV 10th order moved by:	0.976	mm
	10.064	arcsec
.3 keV 2nd order moved by:	0.972	mm
	10.023	arcsec
.3 keV 3rd order moved by:	0.976	mm
	10.064	arcsec

CONCLUSION:

Spectral line displacement due to off-pointing approximates thin lens ("pinhole") behavior.

XGS w/ CAT Grating

Cross-dispersion and Dispersion Direction Image Placement Control Requirement, i.e. Mispointing In, and Normal to, the Rowland Circle Plane



Note: Light green box contributors are zero if a translation stage is used, but the red box (translation stage resolution and setting) is non-zero in this case. Otherwise, if no translation stage is used, red box is zero, and light green contributors are non-zero.

XGS w/ CAT Grating

Cross-dispersion Direction Image Placement Control, i.e. Mispointing Normal to Rowland Circle

- Requirement
  - Combination of CCD alignment to nominal position, and all error contributors that displace the image relative to the nominal position, must root sum square to < +/- 1.6 mm (3σ).
  - Above requirement holds in the cross-dispersion direction
  - Alignment requirement in the dispersion direction is dictated by science requirements which must determine how much of the spectral bandwidth can be "lost" by falling off the ends of the detector.

Courtesy Paul Reid 9/2008

XGS Image Displacement due to Metering Structure Torsion

PROJECTION GEOMETRY

- **Image displacement due to torsion is most prominent at the extreme radius: R=1.6m**
- **Allocation is 1.6 mm / 3.2 arcmin, considering cross-coupling effects of all displacement contributors**
- **To keep images within a "pointing error buffer" of +/- 1.6 mm, the torsion of the Metering Structure must be limited to +/- 3.4 arcmin [arc sin (1.6 / 1600)]**

REQUIREMENT

- **The torsion of the IXO Metering Structure shall be limited to +/- 3.4 arcmin, to keep an XGS image on the XGS CCD Detectors within a +/- 1.6 mm tolerance**

Note: the above requirement may be alleviated by the implementation of an X-Y translation stage for the XGS CCD Camera

Note: one mm corresponds to ~10" at 20m

Rigid Body Effects

Motion of Images

Displacement of Images at the Detectors due to Observatory tilt or to Metering Structure Lateral Translation

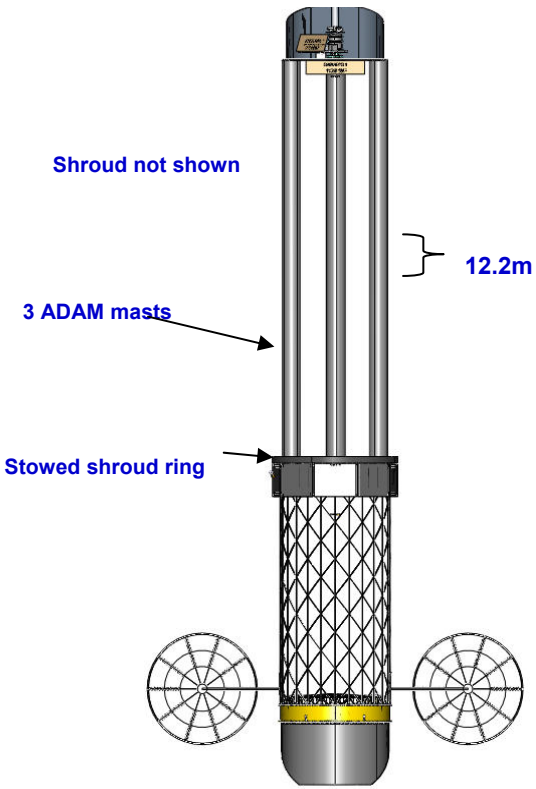
Lateral displacement of the FIP relative to the X-ray Beam will cause the image on the Detectors to move (in the coordinate frame of the Detector). Here is how:

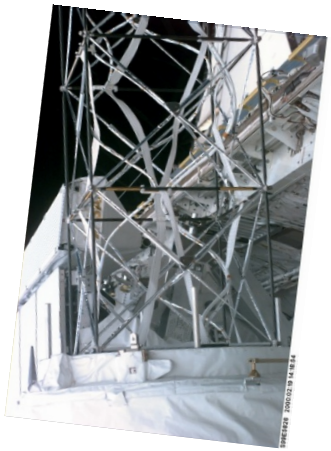
1. **For On-Axis Instruments, displacement of the FIP in any direction will cause the image on the Detector to move an equivalent amount in the opposite direction (in the coordinate frame of the Detector)**
   - **Example: a 1 mm movement of the FIP in the +Y direction will cause the image on the Detector to move 1 mm in the –Y direction (relative to the Detector frame)**
2. **For CAT Gratings CCDs, lateral displacement in the Dispersion direction (~X) will cause the image on the Detector to move approximately an equivalent amount in the opposite direction (in the coordinate frame of the CCD)**
   - **Example: a 1 mm movement of the FIP in the +X direction will cause the image on the Detector to move ~1 mm in the –X direction (relative to the CCD frame)**
3. **For CAT Gratings CCDs, lateral displacement in the Cross-dispersion direction (~Y) will cause the image on the Detector to move an equivalent amount in the opposite direction (in the coordinate frame of the CCD)**
   - **Example: a 1 mm movement of the FIP in the +Y direction will cause the image on the Detector to move 1 mm in the –Y direction (relative to the CCD frame)**
4. **For OP Gratings CCDs, lateral displacement in the Dispersion direction (Y) will cause the image on the Detector to move approximately an equivalent amount in the opposite direction (in the coordinate frame of the CCD)**
   - **Example: a 1 mm movement of the FIP in the +Y direction will cause the image on the Detector to move ~1 mm in the –Y direction (relative to the CCD frame)**
5. **For OP Gratings CCDs, lateral displacement in the Cross-dispersion direction (X) will cause the image on the Detector to move an equivalent amount in the <u>same (!)</u> direction (in the coordinate frame of the CCD; due to the reflection off the grating "mirror")**
   - **Example: a 1 mm movement of the FIP in the +X direction will cause the image on the Detector to move 1 mm in the +X direction (relative to the CCD frame)**

CONCLUSION: All displacement of Images due to Metering Structure Lateral Translation can be budgeted similarly for all Instruments, because although directions vary, magnitudes are approximately the same

Flex Body Effects

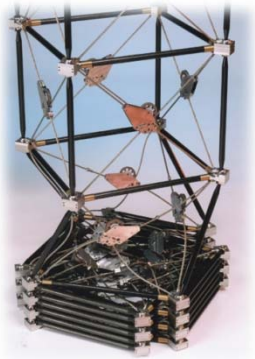
Deployment Module - Implementation of ADAM masts





3 ADAM masts
Stowed Size: 65cm diameter, 1m tall
Longeron CTE = 2*10^-7 / deg C

Longeron Diameter	1.37 cm
Longeron Cross Section Area	1.48 cm^2
Diagonal Cable Nominal Diameter	0.21 cm
Batten OD	1.14 cm
Batten ID	0.91 cm
Bay Length	.308 m
Mast Diameter through longeron centerlines	.592 m
Mast Length	12.2 m
Circle Radius for mast centerlines	1.64 m



Term		Parameters	Unit
Length	Deployed	12.2	m
Mass	Incl. complete 3 Mast System, Internal Harnesses, Deployment Controller, etc.	< 200	kg
Frequencies (from IXO FEM)	1st mode (bending) 2nd mode (torsion)	1.8 4.0	Hz Hz
Power	During deployment Deployed	< 600 0	W W
Push force during deployment / capable of deploying	▪ Instrument module ▪ "Pull-up" multi-layer Telescope Shroud sleeve (4.0 meter dia) w/ two baffles inside ▪ "Pull-up along-the-mast" harness	< 800 < 100 < 100	kg kg kg

Metering Structure Static and Slow Changing Pointing

Deflection calculations based on measured ATK data and CTE Calculations

Term	Definition	Expected Performance (Mast only)	Stat
FIP Torsion (causes Tangential Displacement of CCDs)	Measured on the FIP at r = 1500 cm	**.74 mm (RSS "A " & "B")** .49 mm = 67.4 arcsec torsion due to repeatability lateral deflection .558mm = 67.4 arcsec torsion due to long term drift lateral deflection	**(3σ)**
Full Metering Structure Deflections *(All Static and Slow Changing Effects combined)*	Static and Slow Changing position errors	**< .85 mm** **in X and Y** (est. per calc. below)	**(3σ)**
	Thermal Distortion	**< .15 mm (est'd)in X and Y** (est. per calc. below)	**(3σ)**
Deployable Metering Structure Deflections *(All Static and Slow Changing Effects combined)*	Static and Slow Changing position errors	**.74 mm** (RSS "A " & "B") ▪ "A ": 0.558 mm long term delection for 3 masts ▪ "B": 0.49 mm repeatability deflection for 3 masts	**(3σ)**
	Thermal Distortion	**.1 mm** (arc lengths assumed at full banana shape)	**(3σ)**

Note: one mm corresponds to ~10" (or 1 " to 100 um) at 20m

Defocus Calculations

Term	Definition	Requirement	Expected Performance	Stat
Axial Defocus	**Observatory Focal Length accuracy on Z axis Centerline**	**+/- 0.15 mm** **(Suballocated 50% from 3.0 mm Imaging Error Budget)**	**Full Metering Structure: < 0.08 mm (est'd)** **Depl. Metering Structure contrib.: 0.04 mm** (RSS "A " & "B", add "C" below) ▪ "A ": 0.018 mm 3σ repeatability elongation for a mast ▪ "B": 0.012 mm 3σ long term drift elongation for a mast ▪ "C": .018 3σ elongation for thermal (CTE .2 ppm/degC	**(3σ)**
XGS CCD Tilt (causes Defocus)	**Relative local Focal Length delta between one end of the CAT CCD array at r = 700 mm and the other end at r = 1500 mm**	**+/- 0.15 mm** **(Suballocated 50% from 3.0 mm Imaging Error Budget)**	**Full Metering Structure: < 0.08 mm (est'd)** **Depl. Metering Structure contrib.: 0.04 mm** (at 1.5 m radius, due to same effects as above)	**(3σ)**

Note: one mm corresponds to ~10" at 20m

Deployable Metering Structure Long Term Drift and Repeatability Vendor Data

Mast repeatability and long term drift deflections (thermal distortion is not included)

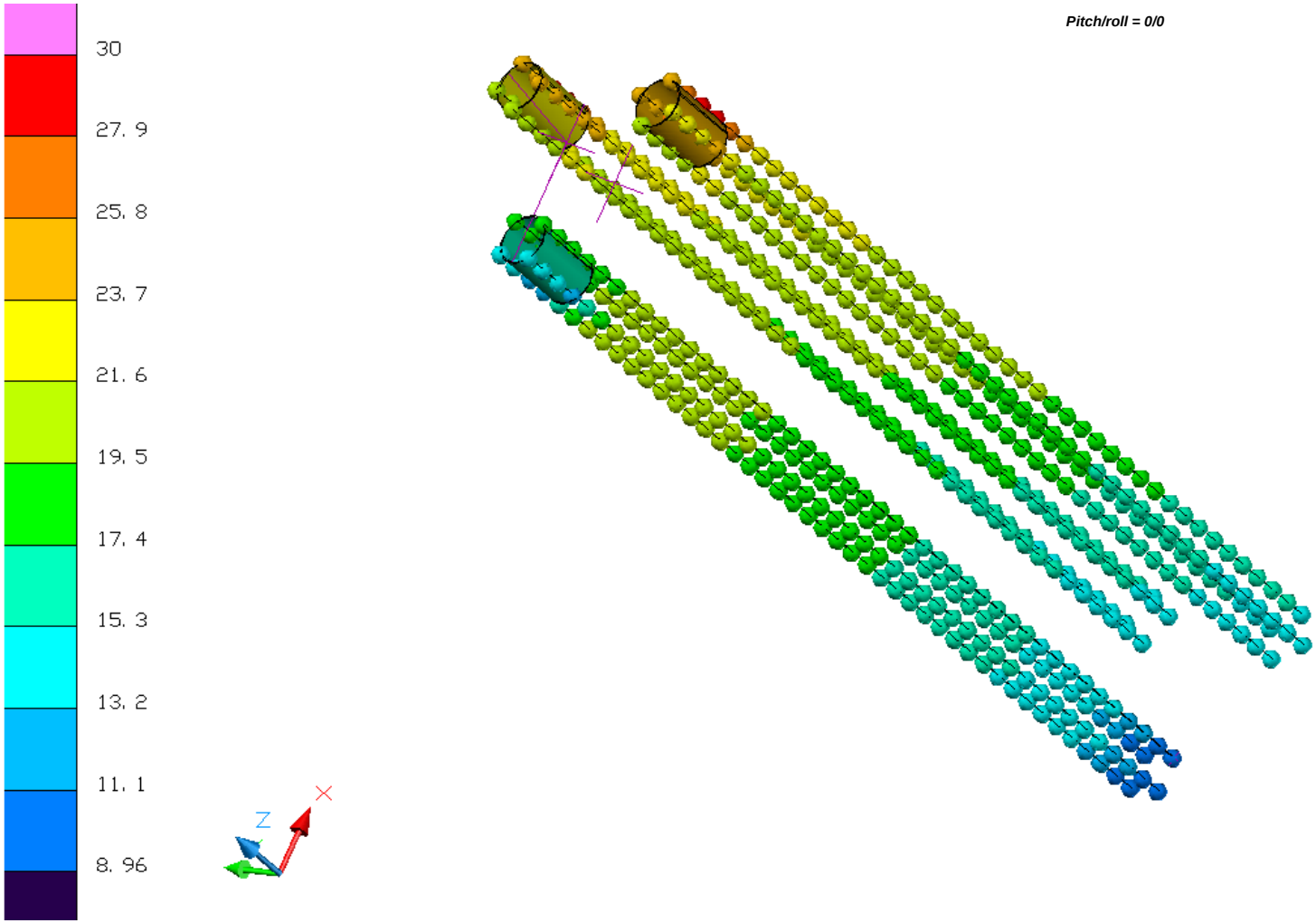
From: Messner, Dave [Dave.Messner@ATK.COM), Sunday, August 03, 2008

- **Long term drift** due to longeron ball seating, longeron coefficient of moisture expansion, diagonal ball seating, diagonal cable hysteresis, and diagonal cable creep**:**
  - **0.97 mm** **3σ lateral deflection for one mast, (mm)**
  - **0.018 mm** **3σ elongation for a mast, (mm)**
  - **0.558 mm** **3σ 3 lateral mast deflection, (mm)**
  - **0.026 deg** **3σ 3 mast twist, (deg) = 1.6 arcmin**
  - **6.6E-04 deg** **3σ 3 mast tip rotation, (deg)**

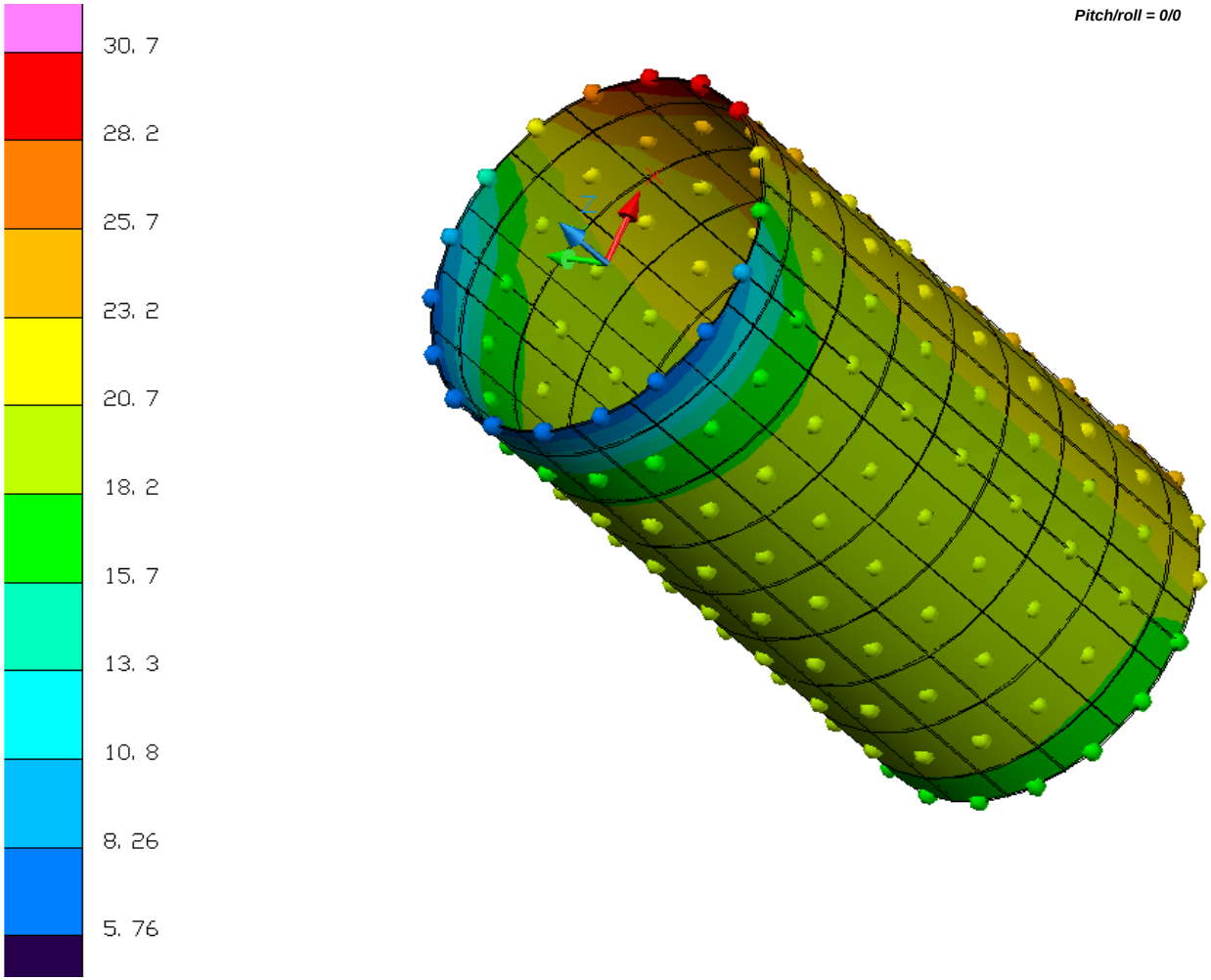
- **Repeatability** due to longeron ball seating, longeron coefficient of moisture expansion, diagonal ball seating, diagonal cable hysteresis, and diagonal cable creep**:**
  - **0.85 mm** **3σ lateral deflection for one mast, (mm)**
  - **0.012 mm** **3σ elongation for a mast, (mm)**
  - **0.49 mm** **3σ 3 mast lateral deflection, (mm)**
  - **0.023 deg** **3σ 3 mast twist, (deg)**
  - **4.5E-04 deg** **3σ 3 mast tip rotation, (deg)**

Note: Repeatability tests conducted on a six-bay engineering mast were within 2 sigma of calculated predictions for that mast.

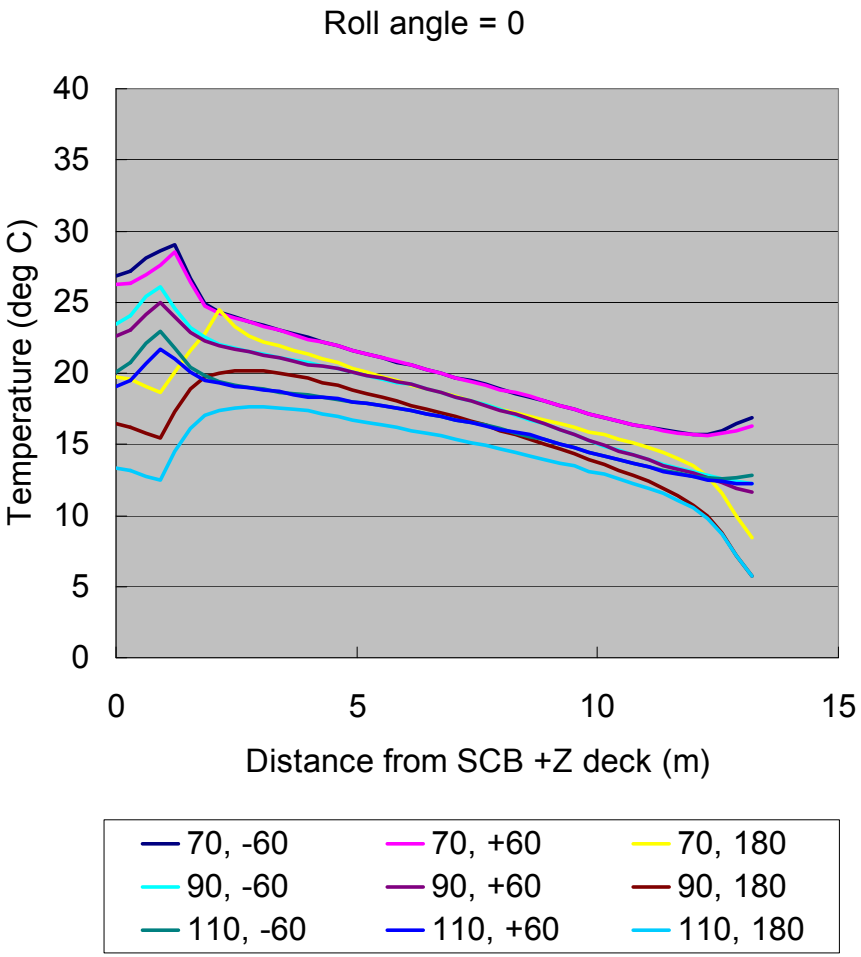
Thermal Distortion Analysis - Mast Temperatures

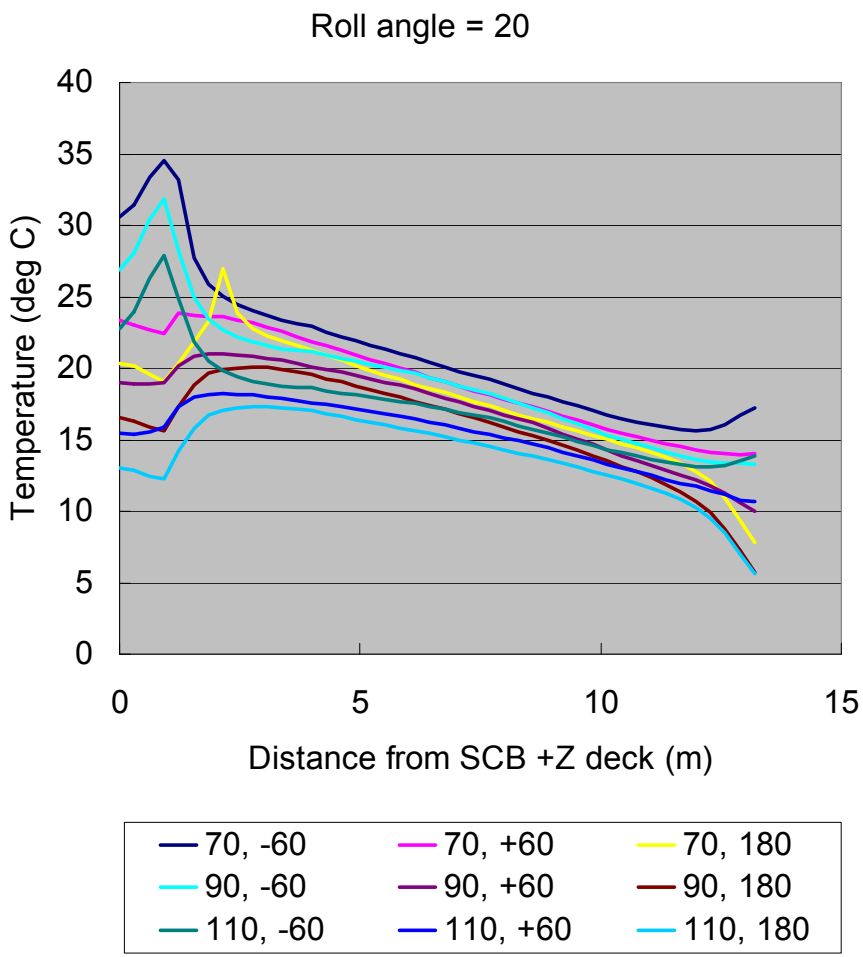


Thermal Distortion Analysis - FMS Temperatures



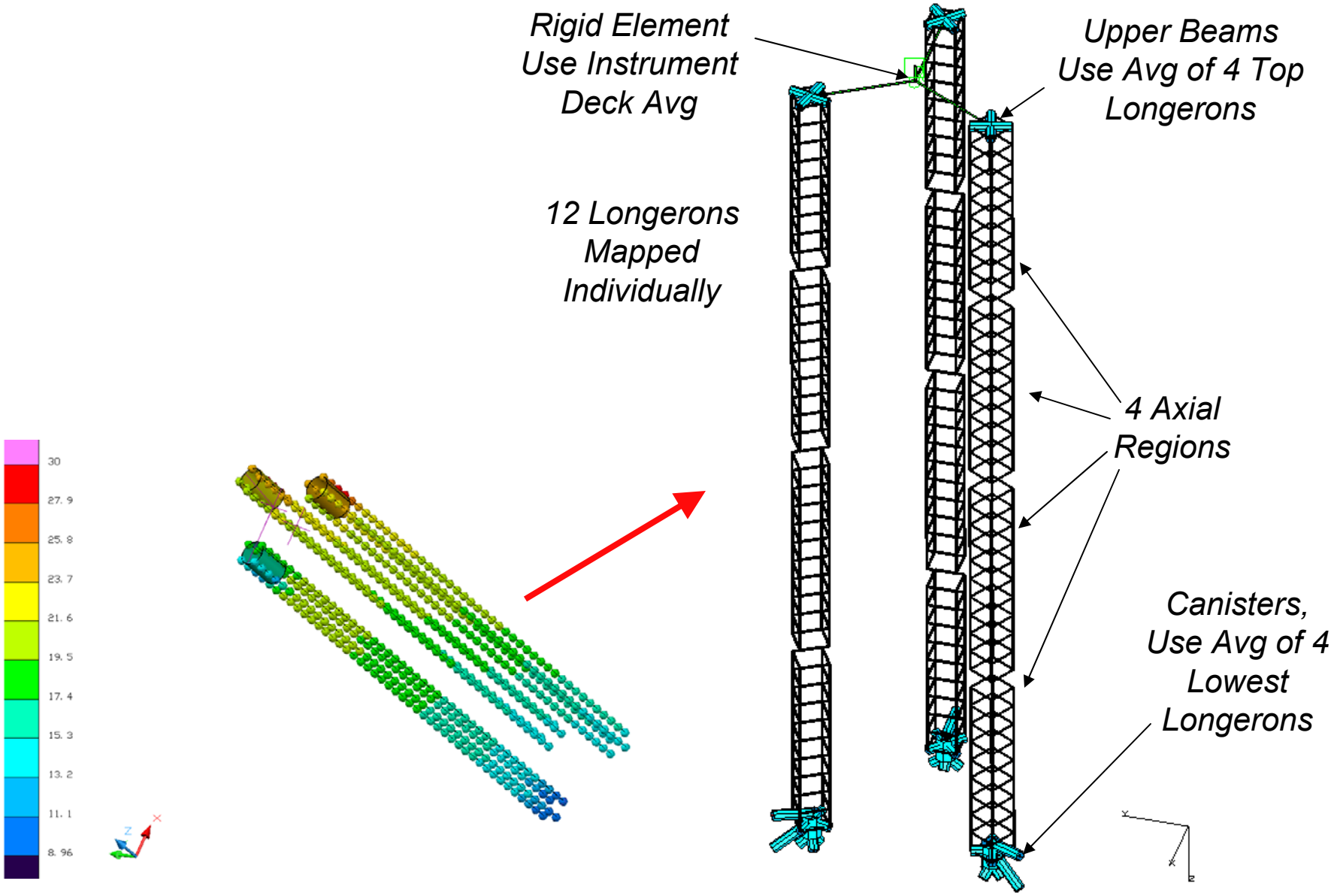
Thermal Distortion Analysis - Mast Temperatures, Numerical Results



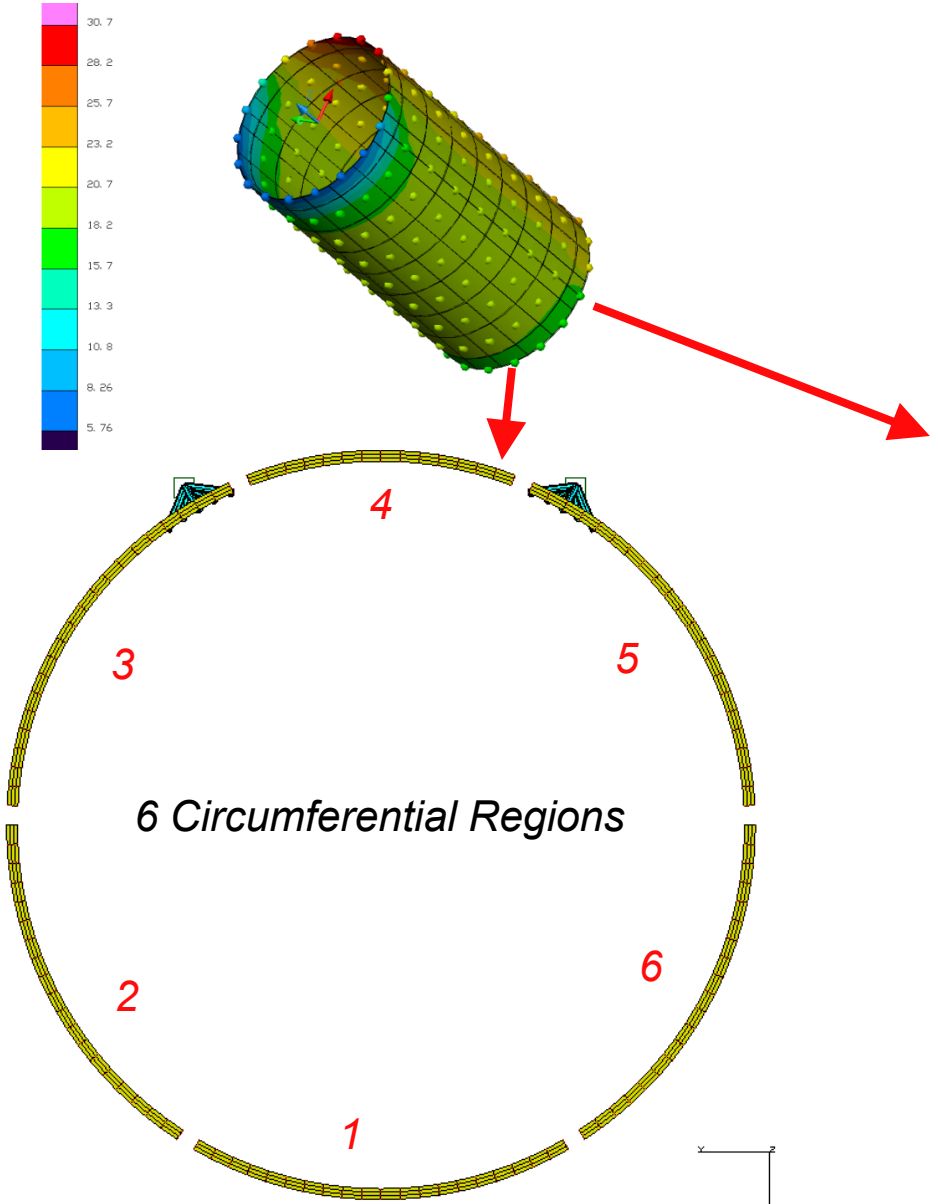


<u>Legend</u>: *First number is pitch angle, measured from telescope axis*
Second number is mast angular position, measured from +X axis

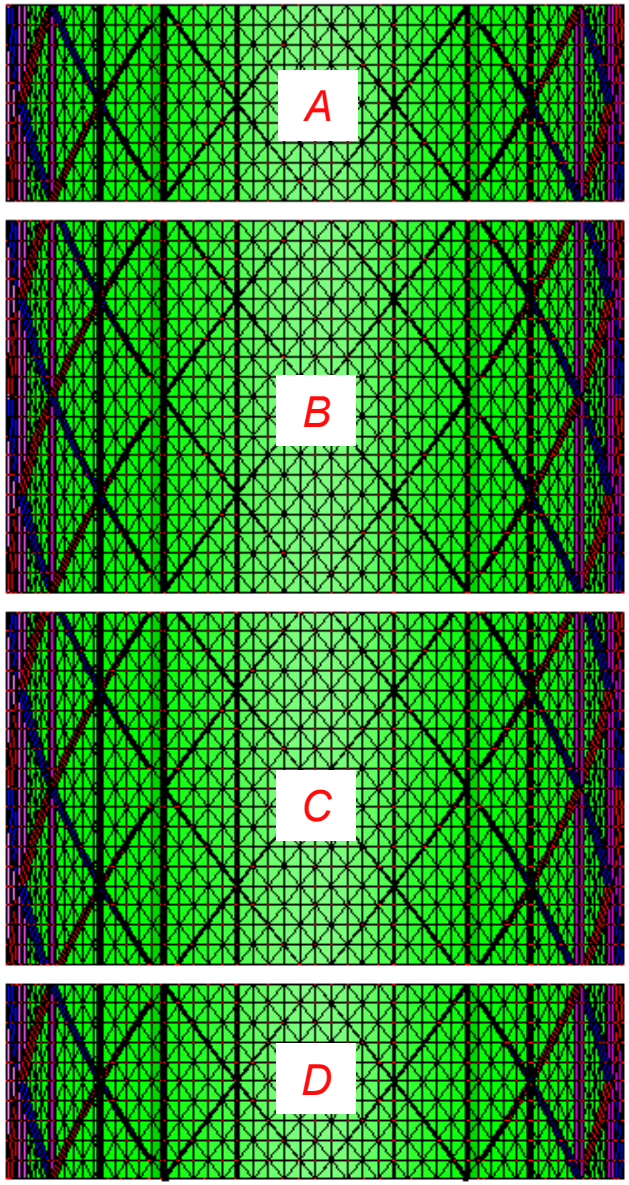
Mast LongeronsTemperature Mapping



FMS Temperature Mapping



4 Longitudinal Regions



Integrated Thermal Distortion Analysis Result

- Model was kinematically restrained at FMA
- Focal Plane image deflections within acceptable limits

Slew From Pitch_0/Roll_0 to Pitch_20/Roll_20

	DISPLACEMENTS						
LOCATION	POINT ID.	X (mm)	Y (mm)	Z (mm)	RX (asec)	RY (asec)	RZ (asec)
FMA Avg	20096	0.0000	0.0000	0.0000	0.000	0.000	0.000
TAD Corner Cube	60857	-0.0001	-0.0002	0.0000	0.003	0.000	-0.015
+Y Star Tracker	60858	0.0036	0.0002	0.0018	1.237	2.688	-0.319
-Y Star Tracker	60864	0.0018	0.0029	0.0022	-1.738	2.312	-0.180
Image on Focal Plane		0.0052	0.0776	-0.0074	1.097	-0.079	0.199

Slew From Pitch_0/Roll_0 to Pitch_-20/Roll_20

	DISPLACEMENTS						
LOCATION	POINT ID.	X (mm)	Y (mm)	Z (mm)	RX (asec)	RY (asec)	RZ (asec)
FMA Avg	20096	0.0000	0.0000	0.0000	0.000	0.000	0.000
TAD Corner Cube	60857	-0.0002	-0.0003	0.0000	0.003	0.000	-0.009
+Y Star Tracker	60858	0.0020	0.0015	0.0010	-0.067	1.110	0.086
-Y Star Tracker	60864	0.0001	0.0021	0.0001	-0.335	0.268	-0.308
Image on Focal Plane		0.0027	0.1018	-0.0134	1.314	-0.035	0.245

Error Budgets

Observatory Level Pointing Knowledge Budget - Top Layer

Image Reconstruction Boresight Pointing Radial Knowledge

Radial Requirement	Expected Performance
1 arcsec radial [HPD]	.54 arcsec [HPD]

RSS

Boresight Offset Knowledge Error

(i. e. TADS error)

Sub-allocated Requirement	Expected Performance
.8 arcsec radial [HPD]	.45 arcsec radial [HPD]

Star Tracker Attitude Knowledge Error

Sub-allocated Requirement	Expected Performance*
.5 arcsec radial [HPD]	.3 arcsec radial [HPD]

** After in flight optical distortion calibrations*

Jitter

(outside of TADS bandwidth)

Sub-allocated Requirement	Predicted Performance
.15 arcsec radial [HPD]	.02 arcsec radial [HPD]

The Requirement for Roll Knowledge is:
- **3 arcsec [HPD]**

The Expected Performance for Roll Knowledge is:
- **2 arcsec [HPD] (stability over a science observation)**

Observatory Level Pointing Control Budget - Top Layer

Telescope Pointing Control Pitch and Yaw

Requirement	Predicted Performance
10 arcsec (3σ)	1.54 arcsec (3σ)

RSS

Pointing Error (Star Tracker + TADS)

Carry-over Requirement	Predicted Performance
1.7 arcsec (3σ)	0.86 arcsec (3σ)

- ** RSS of the TADS and the Start Tracker 3σ numbers*
- *Star Tracker performance after in flight optical distortion calibrations*

Control System Performance

Sub-allocated Requirement	Predicted Performance
9.7 arcsec (3σ)	0.45 arcsec (3σ) per axis

Metering Structure Lateral Translations*

Carry-over Requirement	Predicted Performance
+/- 16 arcsec (1.6 mm)	+/- 12 arcsec (1.2 mm)

- *Includes Static Errors, Slow Drifts, Flex Body Effects, and Jitter*
- *For On-Axis Instruments, image displacement due to Static and Slow Drift Errors can be nulled by "Observatory Offpointing"*

Defocus Budget XGS - Top Layer

Defocus	
Requirement	Predicted Performance
+/- 0.3 mm	0.16 mm

SUM

Axial Defocus (Axial Metering Structure Growth or Shrinking)	
Sub-allocated Requirement	Predicted Performance
+/- 0.15 mm	0.08 mm

Defocus due to FIP Tilt (Defocus of the XGS CCDs at r = 1500 mm)	
Sub-allocated Requirement	Predicted Performance
+/- 0.15 mm	0.08 mm

Metering Structure Lateral Translations Budget for On-Axis Instruments - Top Layer

Metering Structure Lateral Translations

Boresight Misalignment relative to the FMA Optical Axis

Requirement	Expected Performance
+/- 3 mm (30 arcsec)	+/- 1.001 mm (10 arcsec)

RSS

Lateral Translation due to Metering Structure Static and Slow Changing errors

(incl. Thermal induced deflections)

Sub-allocated Requirement	Expected Performance*
+/- 2.9 mm	+/- 1.0 mm

Jitter

(outside of TADS bandwidth)

Sub-allocated Requirement	Predicted Performance
+/- 0.02 mm	+/- 0 .002 mm

- *Metering Structure lateral translations cause FMA Optical Axis to Boresight Misalignment that contributes to image quality degradation (is a term in the Imaging Error Budget)*

- *For all "on-axis" Instruments, mis-pointing induced by Metering Structure lateral translations is nulled by "Observatory off-pointing".*
- *For the XGS, Metering Structure Lateral Translations do contribute mis-pointing. To null those mis-pointing errors, an X-Y Translation Stage is used.*

Metering Structure Lateral Translations Budget for XGS CCDs - Top Layer

Metering Structure Lateral Translations

Boresight Misalignment relative to the FMA Optical Axis

Requirement	Expected Performance
+/- 1.6 mm (30 arcsec)	+/- 1.2 mm (12 arcsec)

RSS

Lateral Translation due to Metering Structure Torsion*

(Worst case for CCDs at r = 1500 mm incl. Thermal induced deflections)

Sub-allocated Requirement	Expected Performance
+/- 1.0 mm	+/- 0.74 mm

- **** contributes only to XGS CCD displacement, but not to on-axis Instruments***

Lateral Translation due to Metering Structure Static and Slow Changing errors

(incl. Thermal induced deflections)

Sub-allocated Requirement	Expected Performance*
+/- 1.25 mm	+/- 1.0 mm

Jitter

(outside of TADS bandwidth)

Sub-allocated Requirement	Predicted Performance
+/- 0.02 mm	+/- 0.002 mm

- *Metering Structure lateral translations cause FMA Optical Axis to Boresight Misalignment that contributes to image quality degradation (is a term in the Imaging Error Budget)*

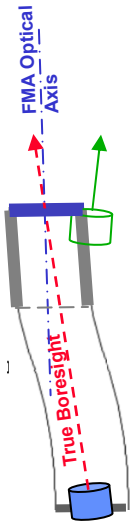
- *For all "on-axis" Instruments Metering Structure lateral translations induced pointing error is nulled by "Observatory Off-pointing".*
- *For the XGS, Metering Structure Lateral Translations do contribute the pointing error. To null thaat error, an X-Y Translation Stage is used.*

Focus and Translation Mechanisms

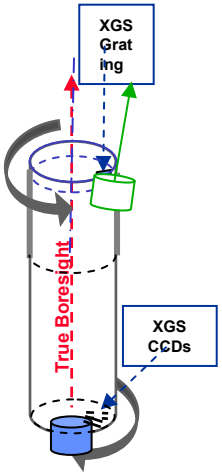
- **Focus (+/-Z) Mechanism for XMS and WFI/HXI**
  - Max. Allowed On-axis Defocus in Z: +/- .15 mm
  - Expected total Metering Structure On-axis Defocus due to all effects in Z: +/- .08 mm
  - Focus Mechanism range of motion in Z: +/- 5 mm
  - Note: On-axis Instruments don't need a Translation Mechanism, Metering Structure lateral translations induced pointing error is nulled by "Observatory Off-pointing".

- **Focus (+/-Z) Mechanism for the XGS**
  - - Max. Allowed On-axis + FIP Tilt Defocus in Z: +/- .3 mm
  - - Expected total Metering Structure On-axis + FIP Tilt Defocus due to all effects in Z: +/- .16 mm
  - - Focus Mechanism range of motion in Z: +/- 5 mm

- **Cross-dispersion direction Translation Mechanism for the XGS** (+/- Y for the CAT XGS, +/-X for the OP XGS)
  - Max. Allowed Cross-dispersion direction translation (in X for the OP) : +/- 1.6 mm
  - Expected total Metering Structure Cross-dispersion direction translation due to all effects (in X for the OP): +/- 1.2 mm
  - Translation Mechanism range of motion in one single axis: +/- 10 mm
  - Note: No translation mechanism is needed for the dispersion direction (+/-X for the CAT XGS, +/-Y for the OP XGS).



Sine Mode



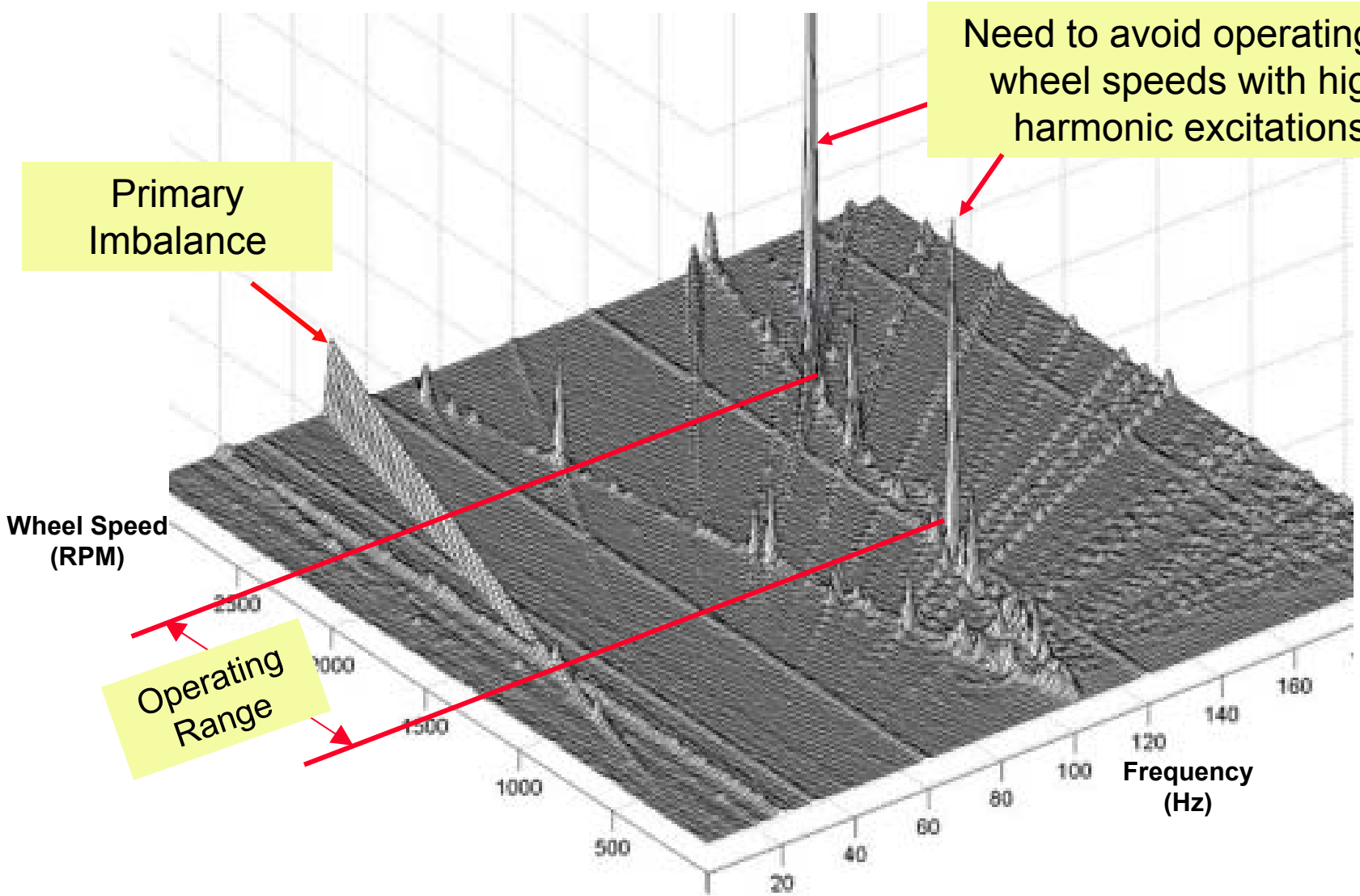
Torsion Mode

Control System Performance

ACS Performance

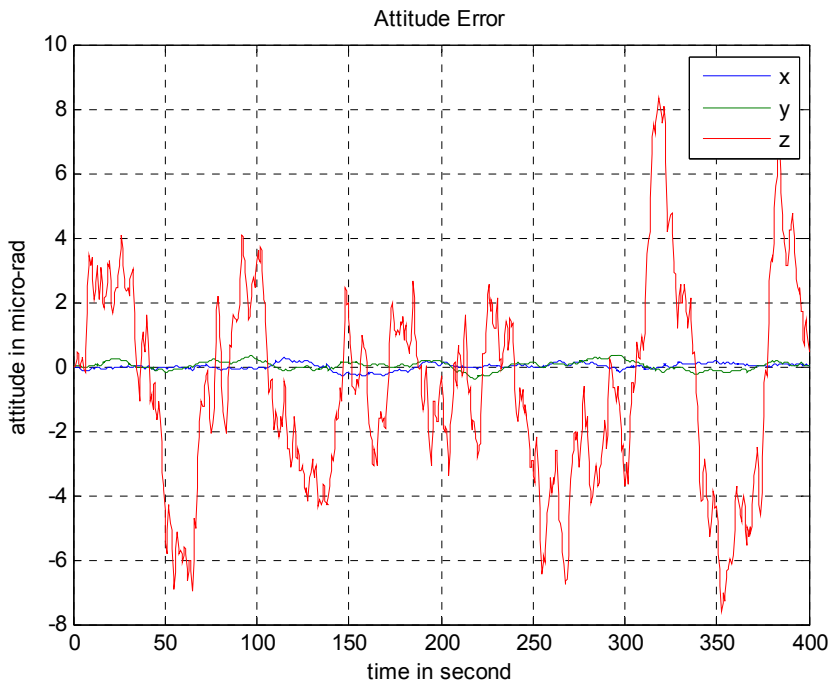
- Mass Properties
  - Ixx = 320,000 kgm^2
  - Iyy = 320,000 kgm^2
  - Izz = 1 2,000 kgm^2
- AST-301 Star Tracker Characteristics (used on Spitzer Space Tel)
  - NEA = 0.15 arcsec about X and Y axes, 4 arcsec about Z axis
  - 2 Hz output
  - 1 sec total latency (from center of integration to application of control torque)
- RWL Torque Capability per Axis: 0.2 Nm (conservative)
- Digital Control (PID) with 0.02 Hz Bandwidth
  - Uses Star Tracker Exclusively (gets better with Gyro, e.g. SIRU)

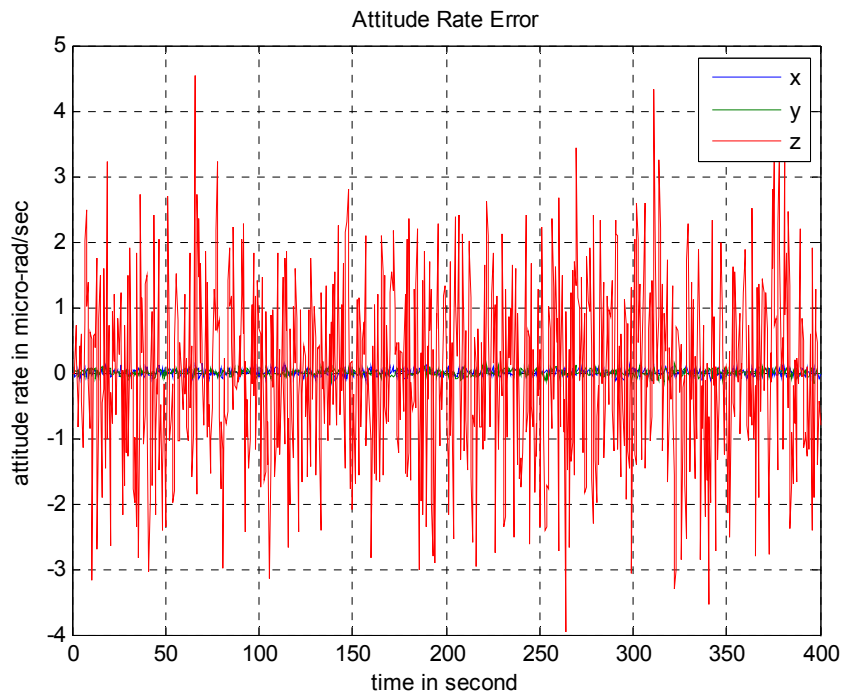
Reaction Wheel Disturbance Forces



Example Carpet Plot of In-plane Imbalance Forces From HR14 Dynamic Test

Pointing Performance

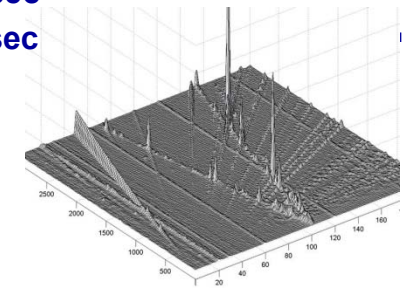




Spacecraft attitude errors due to LC

- **About X (1 sigma) = 0.025 arcsec***
- **About Y (1 sigma) = 0.025 arcsec**
- **About Z (1 sigma) = 0.64 arcsec**

**** Note: 1 arcsec = 4.85 micro-rad***



Spacecraft rate errors due to LC

- **About X (1 sigma) = 0.01 arcsec/s**
- **About Y (1 sigma) = 0.01 arcsec/s**
- **About Z (1 sigma) = 0.3 arcsec/s**

Analyses performed by Ich Pham (LMATC)

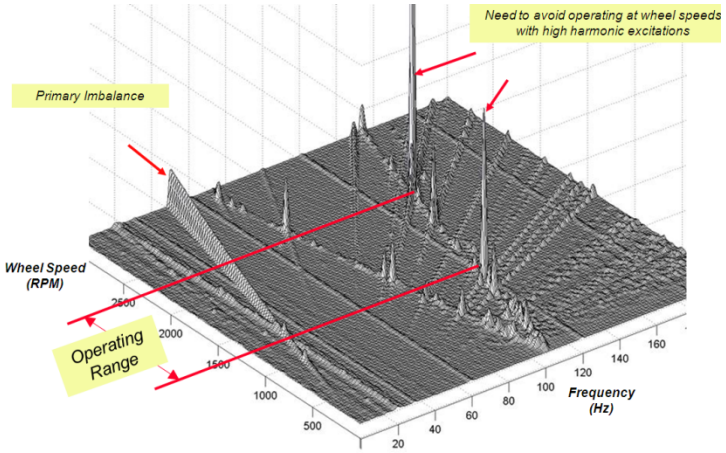
Slew Capability

- Calculated for four Honeywell HR16 wheels
  - In pyramid configuration (like Spitzer)
  - Pyramid apex in X direction
  - 30 deg cant angle (can be optimized depending on yaw (± 180 deg) versus pitch (± 20) slew requirements)
- Each wheel
  - Angular momentum capability: 150 Nms
  - Torque capability: 0.2 Nm (is function of speed)
- Slew speed
  - 60 deg yaw: 0.52 hrs (margin not included)
  - 20 deg pitch: 0.41 hrs (margin not included)

Jitter

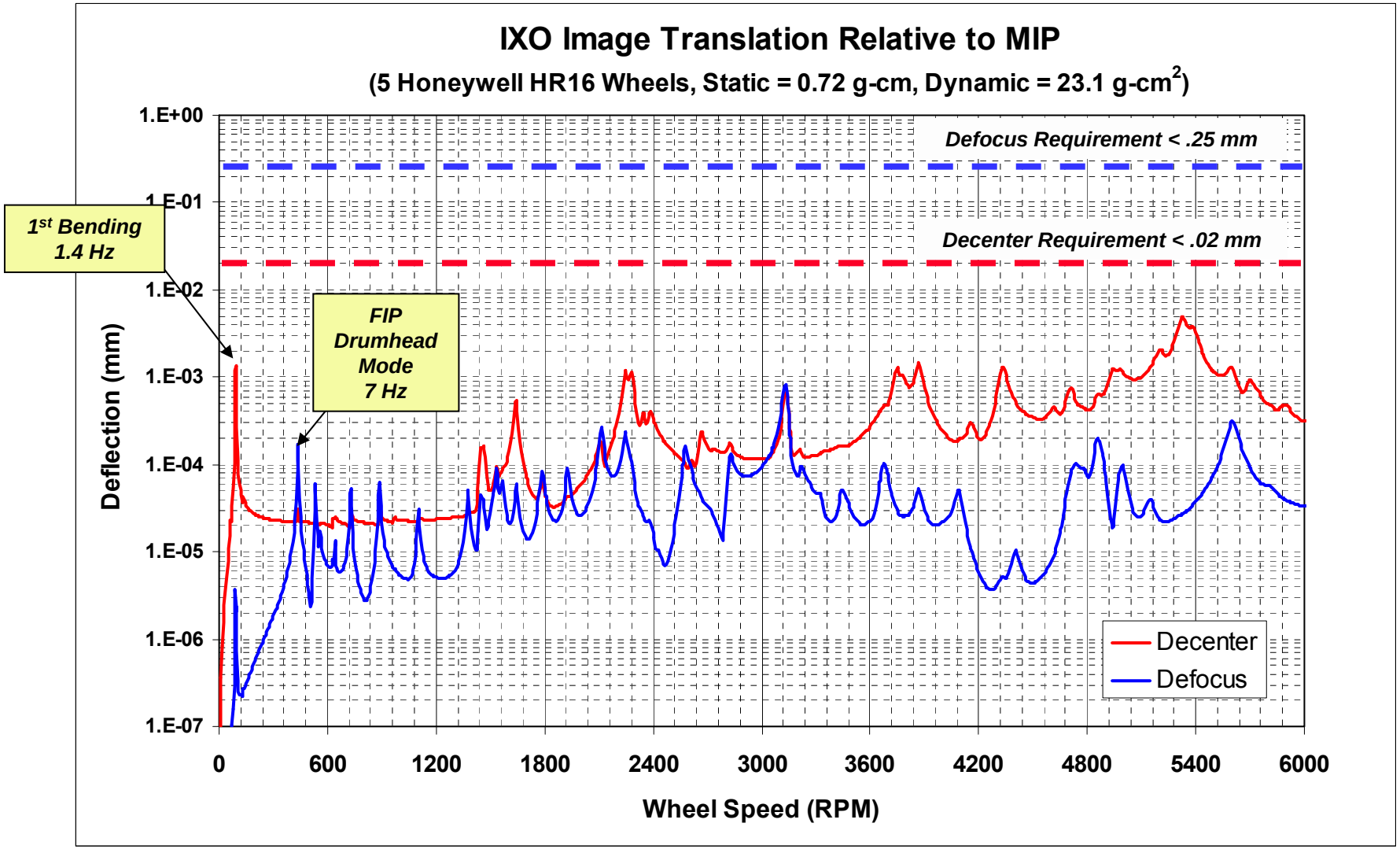
Jitter Analysis Parameters

- 150 N-m-s HR16 Wheel Imbalances (derived from datasheet)
  - Static = .72 g-cm, Dynamic = 23.1 g-cm^2
  - Only primary imbalance considered
  - Refined analysis will include affects of higher harmonics
- Use 0.5% modal damping
- Apply disturbances to all 5 wheels
  - RSS all wheels (conservative: assumes all wheels operate at same speed)
  - Calculate optical element jitter and LOS pointing error versus wheel speed



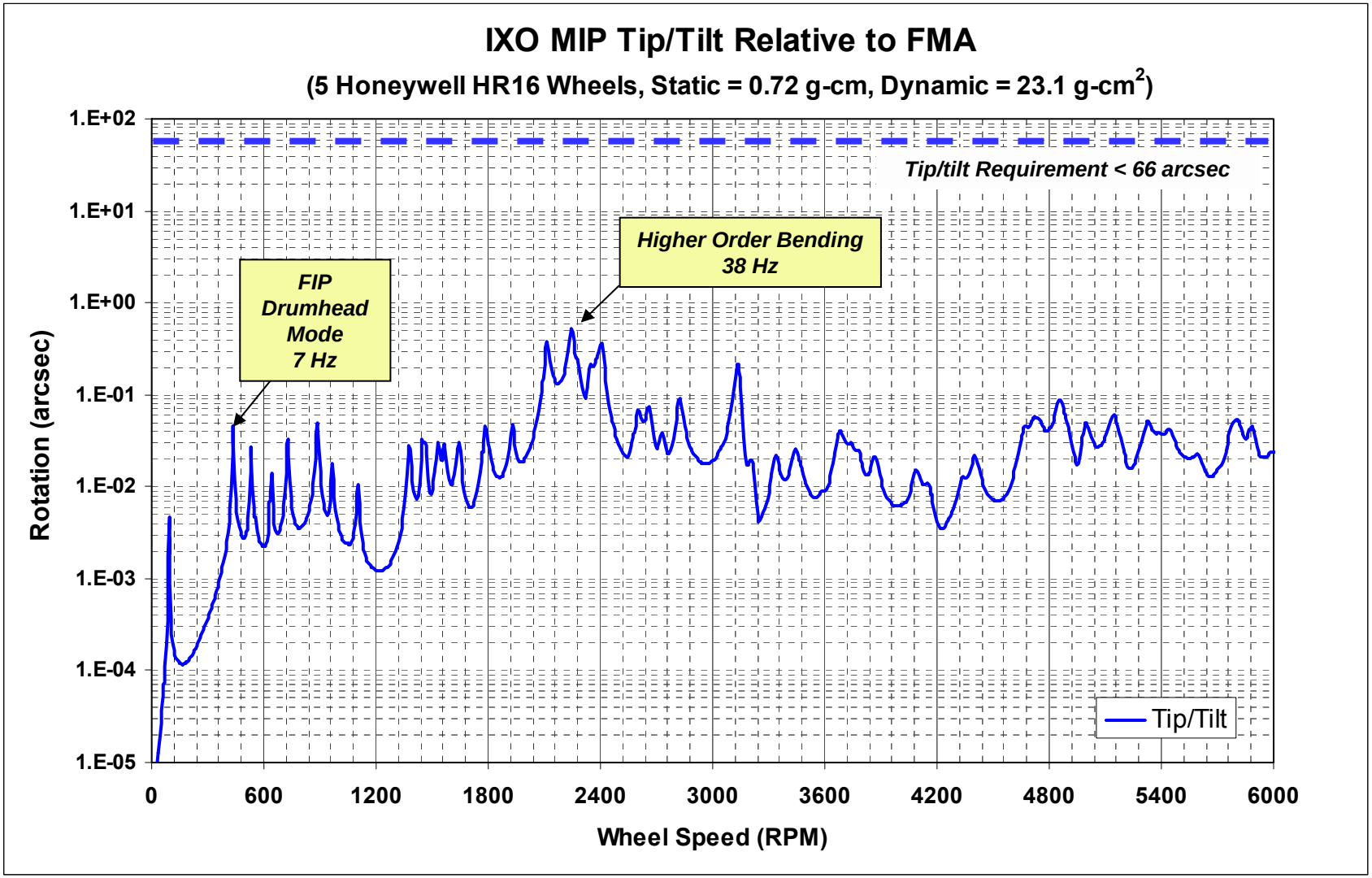
Example Carpet Plot of In-plane Imbalance Forces From HR14 Dynamic Test

Jitter Analysis Results



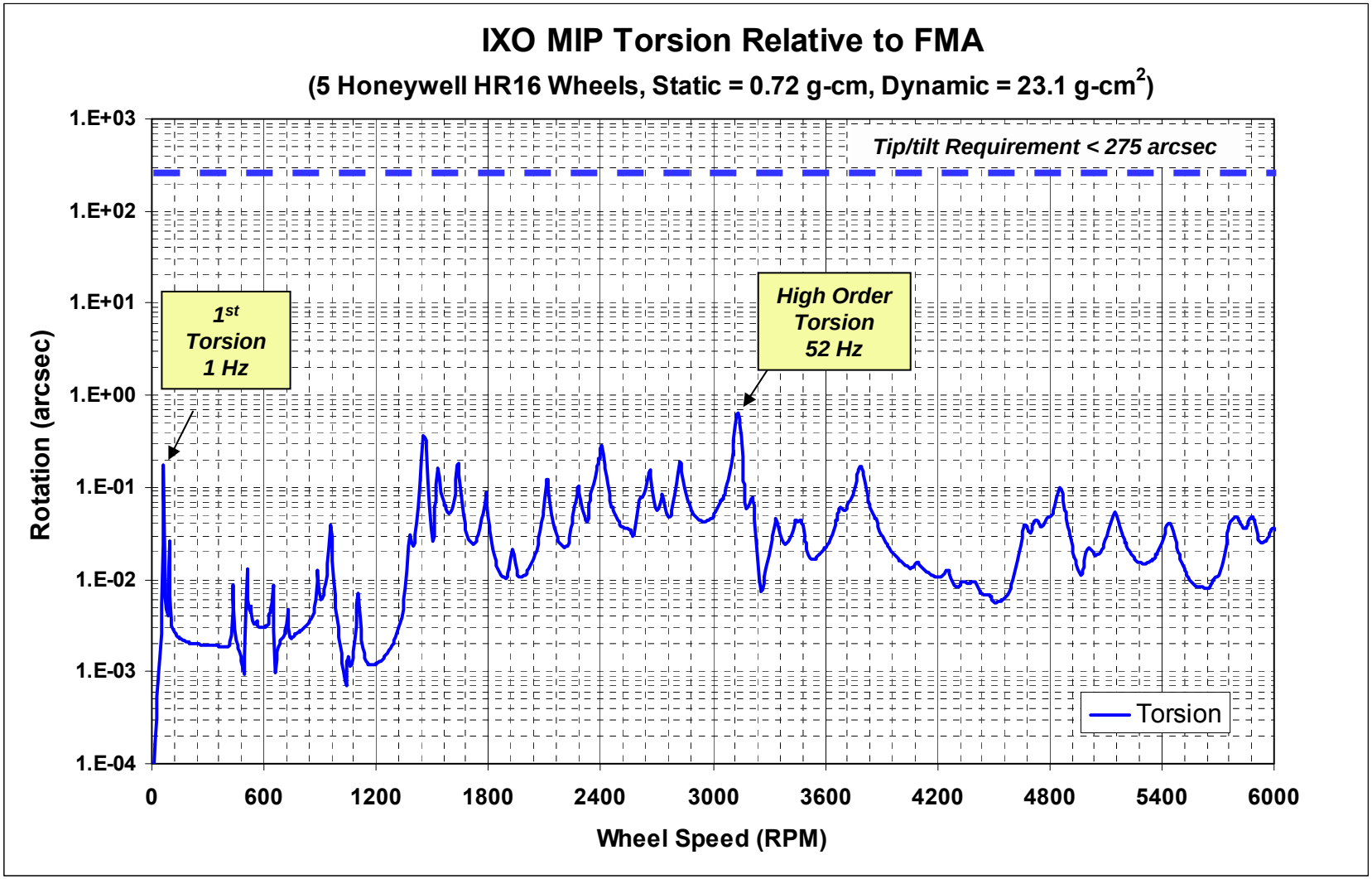
Responses < Requirements

Jitter Analysis Results (Tip / Tilt)



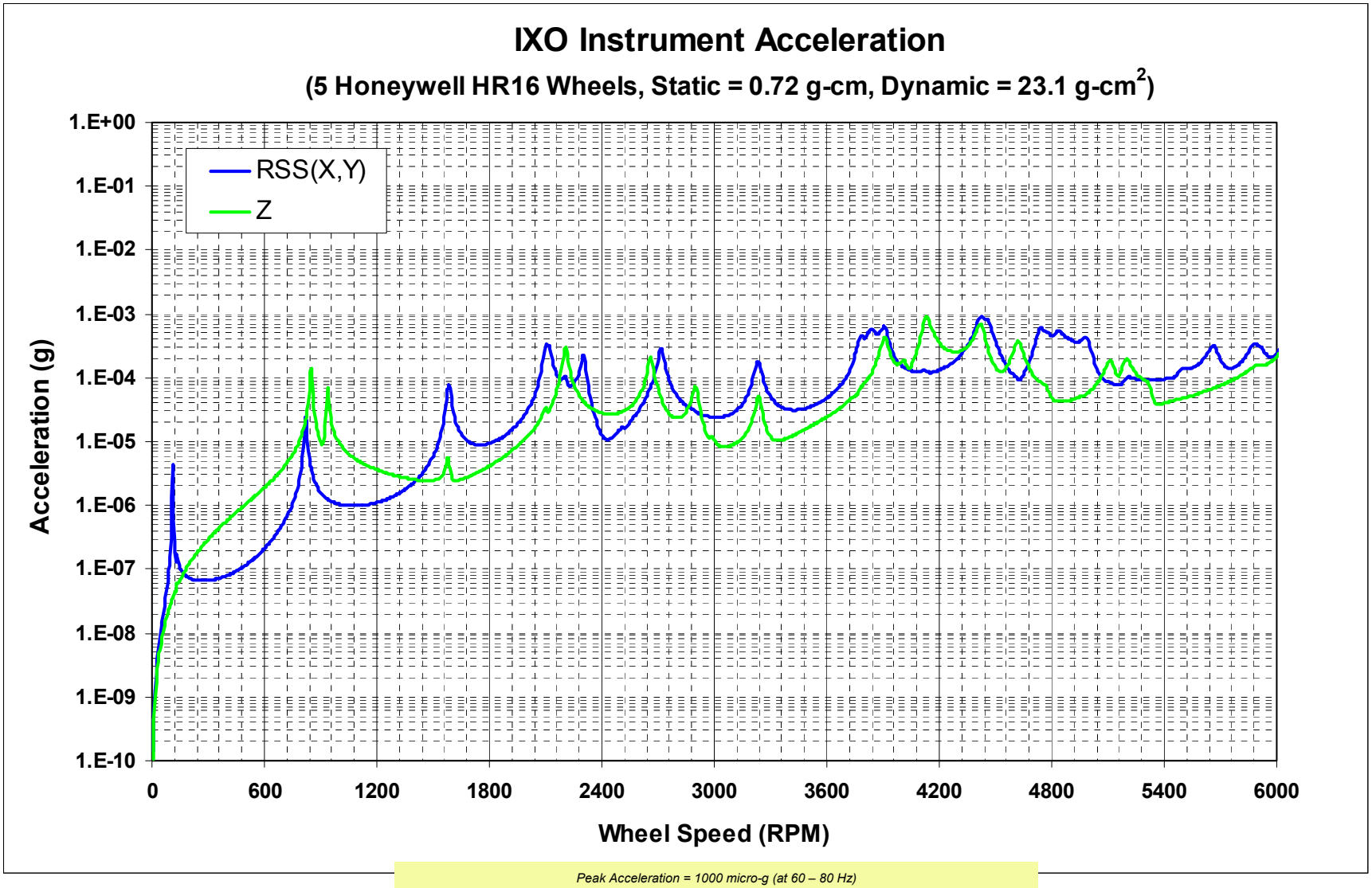
Responses << Requirement

Jitter Analysis Results (Torsion)



Responses << Requirement

Instrument Accelerations



Peak Acceleration = 1000 micro-g (at 60 – 80 Hz)

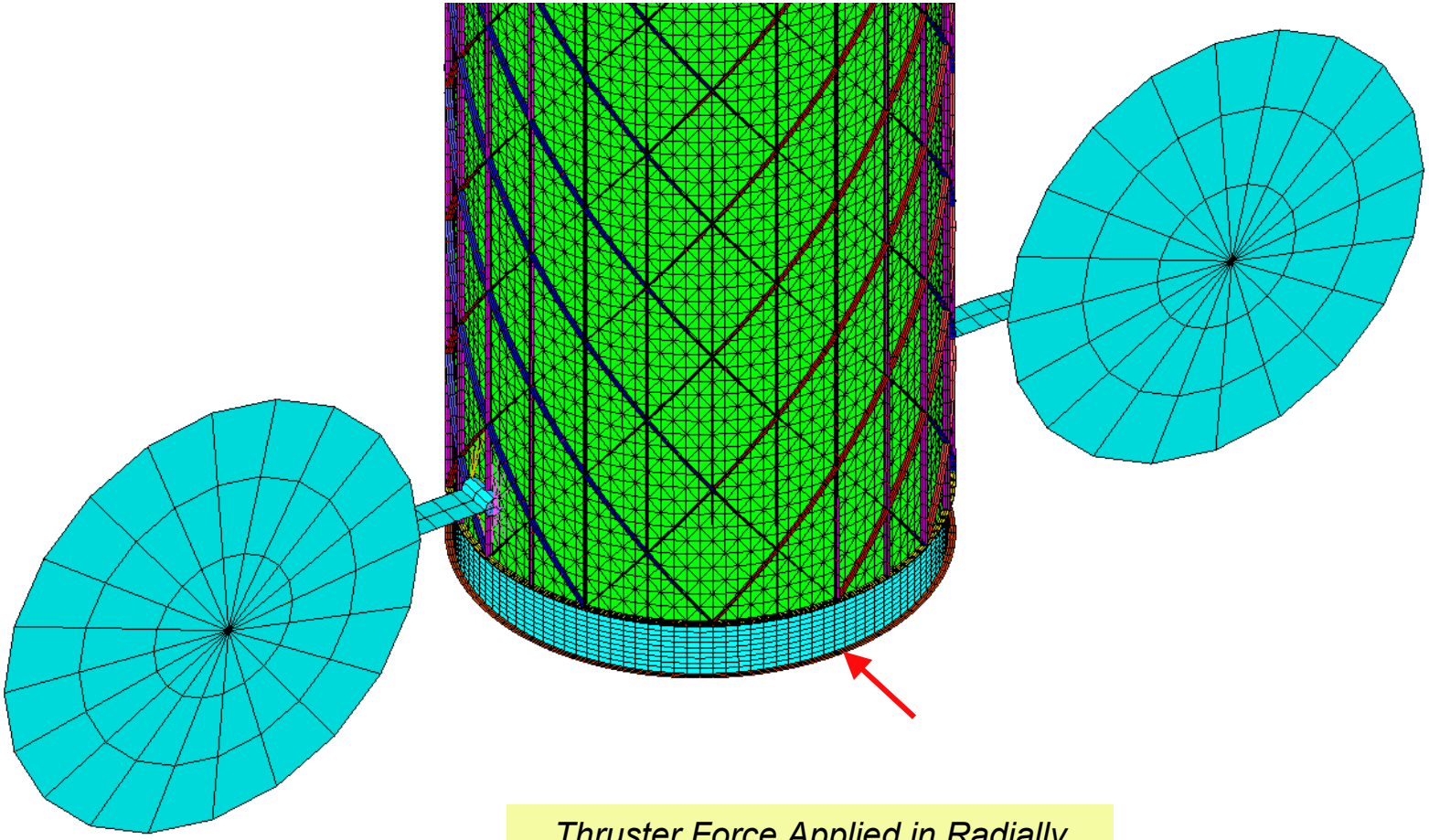
0.9 N Thruster Firing Effects

Impact of Solar Pressure Offload (0.9 N Thruster) Firing

- Use highly reliable MR103H Aerojet thruster used for Voyager and Cassini
- Attitude Deviation versus Pulse Length
  - 0.11 s burn every 18 minutes: 0.165 arcsec deviation
- Number of 0.11 s Thruster Firings:
  - 300,000 over 10 Years (once per 18 min)
    - Voyager had 500,000 burns from single thruster, using same thruster
  - Total amount of propellant: 15 kg
- Assumes IXO config with two 3.35 m dia Circular Ultraflex Solar Arrays

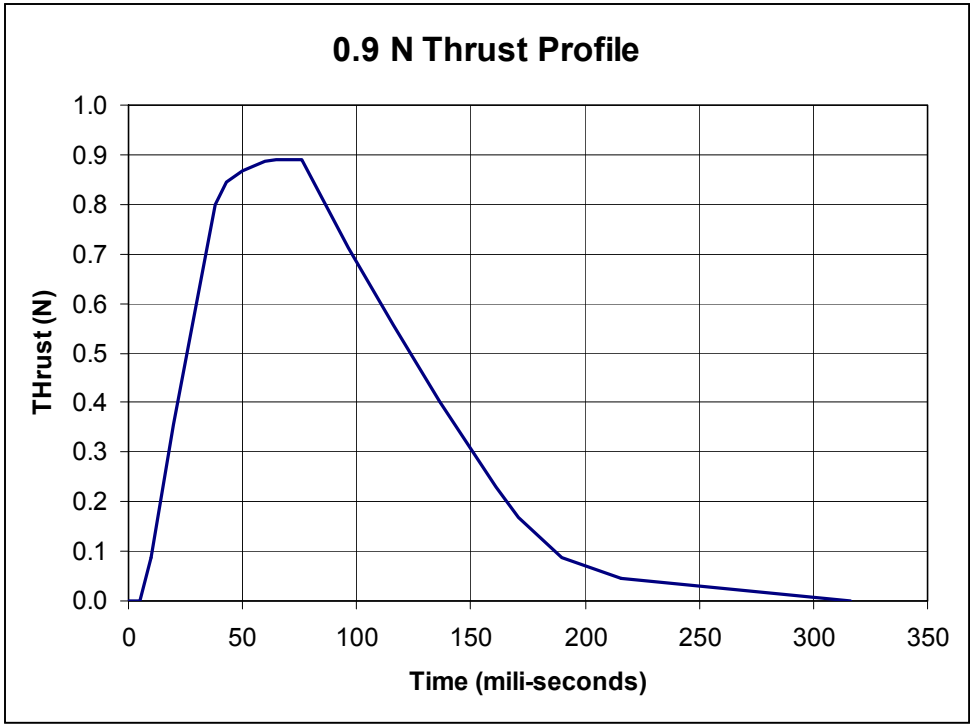
0.9N Thruster Force

- **Use highly reliable MR103H Aerojet thruster used for Voyager and Cassini**



Thruster Force Applied in Radially Inward Direction to +X Side of Spacecraft Adapter Flange

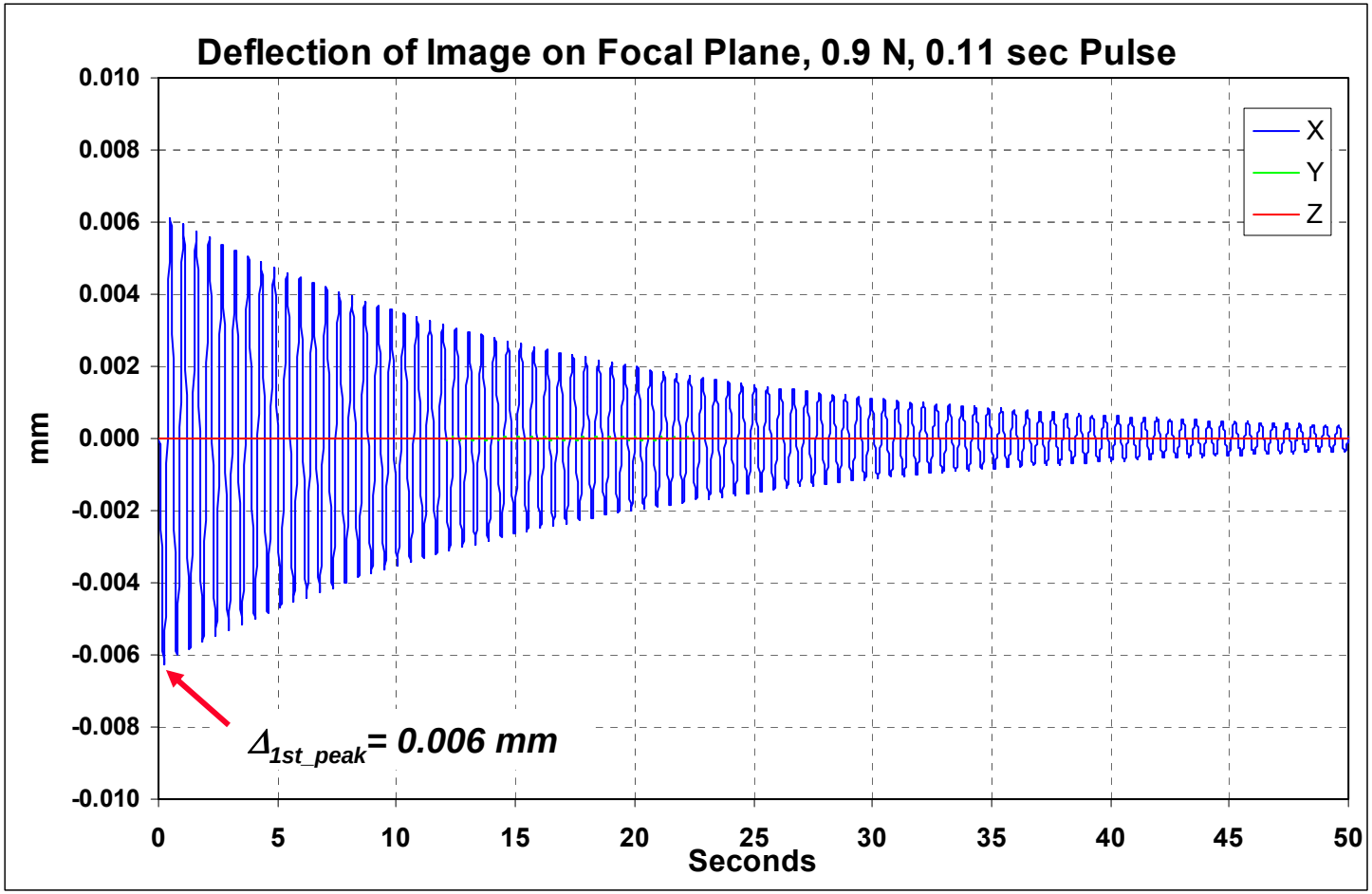
0.9N Thruster Pulse and Model Parameters



Total Impulse = 0.1 N-s
Derived from Astrolink jitter analysis profile

- **Modal damping = .5% of critical damping**
- **232 modes included in solution space (0 to 150 Hz range)**
- **2500 time steps at .001 second per step**

0.9N Thruster Firing Induced Vibration Decay

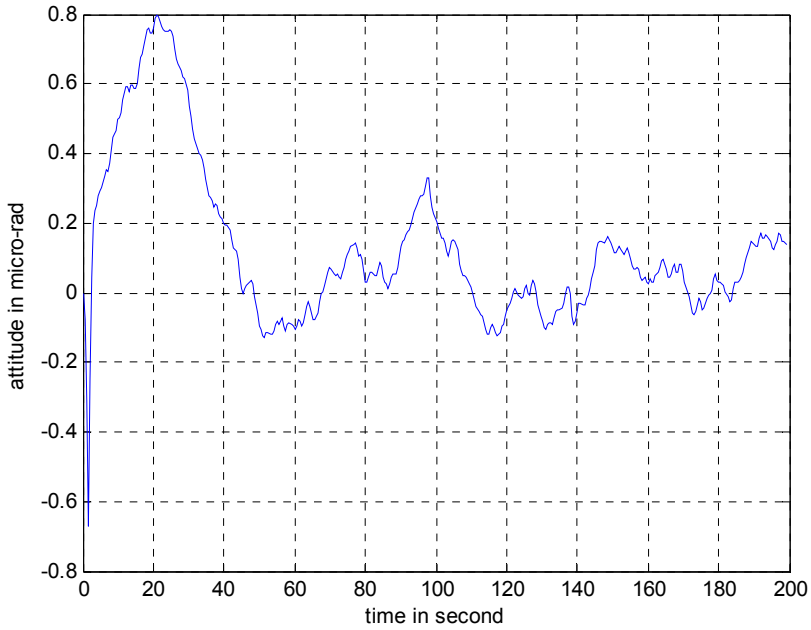


$$\frac{\Delta_{nth_peak}}{\Delta_{1st_peak}} = e^{-2\pi n\xi/(1-\xi^2)^{1/2}} \Rightarrow \Delta_{peak_at_time_t} = 0.006e^{-.0575t}$$

Deflection Decays to less than .001 mm after 30 seconds

0.9N Thruster Firing Induced Temporary Attitude Deviation - Integrated FEM + Control System Result

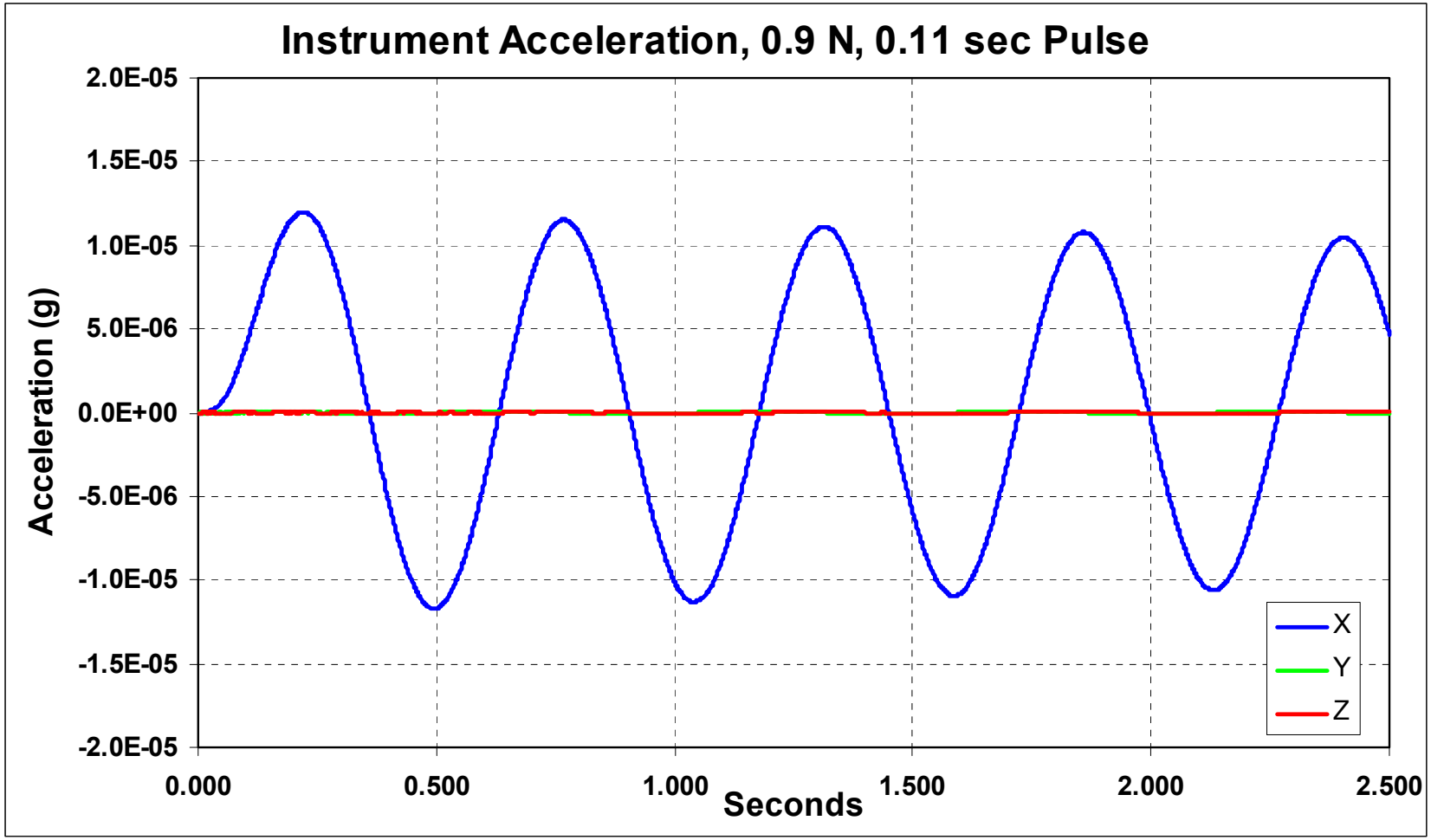
- 0.9 N Thruster on for 0.11 s; generates 0.1 Ns impulse and 0.62 Nms angular momentum delta
- RWL feed forward of -0.2 Nm for 3.1 seconds
- Thruster firing centered relative to 3.1 second RWL feed forward period



- Resulting attitude excursion about Y axis: 0.165 arcsec

Integrated FEM + Control System Result

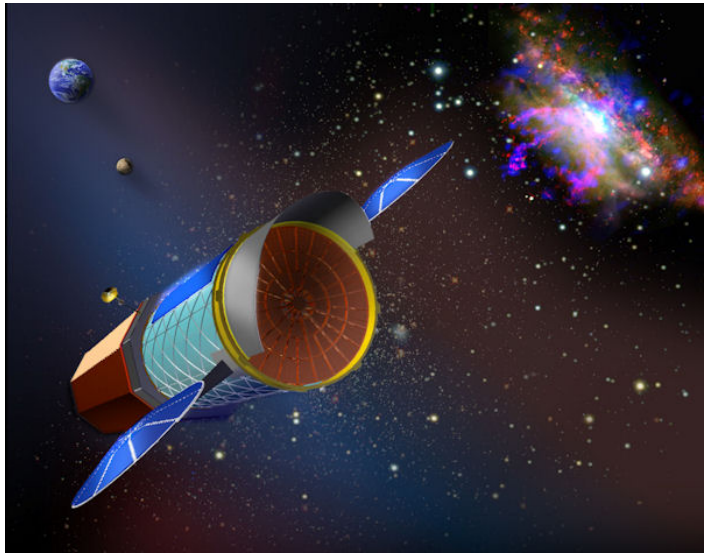
Accelerations due to 0.9 N Thruster Firing



Peak Acceleration = 12 micro-g

IXO Observatory Definition Document
Appendix D

Integration and Test



I&T Purpose and Scope

- Develop and Verify Command and Telemetry Database,
  - All Commands and Telemetry Must be Exercised at Least Once
- Maintain a Safe Environment For I&T Personnel and Flight H/W
- Maintain the Cleanliness Conditions for the IXO S/C & Instruments
- Verify all Flight Mechanical and Electrical Interfaces
- Perform Environmental Qualification of the IXO Observatory
- Verify Observatory Performance Requirements are Met Throughout the Environmental Test Program, Including (to the extent possible) Instrument Performance in Thermal Vacuum
- Verify Observatory Compatibility with IXO Mission Operations Systems
- Make IXO Ready For Launch, assist in integration to launch vehicle.

I&T Assumptions

- At each assembly level, the hardware structures to be assembled are delivered fully qualified.
- The S/C bus will be integrated with the metering structure to form the spacecraft module.
- The spacecraft module will then be integrated with the deployment module.
- Lastly, the instrument module and the optics module will be added to form the observatory.
- The observatory will be tested fully extended in a thermal-vac chamber, in the vertical position. Testing during thermal-vac should include, if possible, alignment testing using an X-ray source (but no focus testing).
- Optical (or UV) GSE collimated sources will operate with a compatible detector on the Movable Instrument Platform to monitor system level mirror and alignment performance
  - A fifth stop position would position the GSE detector at mirror focus
- The observatory will not undergo vibration testing, due to concerns about overstressing the flight mirror assembly.

Models Philosphy

- In accordance with NPR 8705.4 Risk Classification for NASA Payloads for a Class A mission
- Engineering model hardware for new or significantly modified designs will be used.
- Protoflight hardware (in lieu of separate proto-type and flight models) except where extensive qualification testing is anticipated.
- Spare (or refurbishable prototype) hardware as needed to avoid major program impact

Calibration, Focal Plane Stimulators

- Calibration sources in X-Ray are not compatible with full-up observatory configurations
  - All calibration with X-Ray sources must be in vacuum
  - Collimated calibration sources require long distances
  - Collimated large aperture calibration sources require large facilities
- Full X-ray and optical characterization of the FMA is done prior to Observatory I&T
  - During Observatory I&T, alternate optical sources will be used to monitor optical stability
- Instrument Calibration performed prior to deliver to I&T
  - In some cases, instruments may need to be calibrated with the flight FMA
- At Observatory I&T, a combination of sources will be used to monitor end to end performance
  - Optical (visible, UV) Sources
    - Collimated, useful for measure of focus to visible/UV GSE detector on MIP
    - Used in vacuum and ambient conditions
  - X-ray Sources
    - Uncollimated, most useful for throughput measurements with flight instruments
    - Only used in vacuum
    - Electron gun with metal target – Manson Source
    - Radioactive sources
    - Detected by flight science instruments
  - The TADS and external optical metrology
    - Linked to FMA and instrument relative alignment
    - Ambient and vacuum

Contamination

- Rigorous contamination control including special filtration, constant mirror purge, continuous real time monitoring, scheduled cleanings and black light inspections.
  - Preserves science integrity. Must be considered in selection, configuration and operation of facilities, cost driver, schedule driver.
- X-ray point source GSE used to monitor contamination in optical path, especially FMA.
  - Gives realistic measurement of science degradation, indicate contam event.
- Final S/C environmental testing performed with no mass simulators, mockups, protoflight units etc.
  - Enables Test as you fly, demonstrates self compatibility, more important since end-to-end science testing not possible.
- Structural verification model (2nd flight like structure) built and used for modal surveys, to verify structure models, to practice alignments w/o risking contamination on flight structure.
  - Reduces Risk

GSE Required for I&T effort

Equipment	Purpose	Provider
Electrical Ground Support Equipment (EGSE)	**Electrical control and testing of the S/C (i.e. Umbilical console)**	**Electrical Subsystem**
Spacecraft Ground Support Equipment (SGSE)	S/C command, control, and telemetry (i.e. ASIST workstations, front end data processing & distribution, archiving, other IT equipment)	I&T
Mechanical Ground Support Equipment (MGSE)	**Ground handling and transportation (i.e. Dollies, slings, access scaffolding, rotation fixtures, environmentally controlled transporter, etc.)**	**Mechanical Subsystem**
Power GSE	**Support, control and/or simulate power system components (i.e. Solar array simulator, battery simulator, battery AC, battery GSE)**	**Power Subsystem**
Alignment Ground Support Equipment (AGSE)	**Aligning spacecraft components and instrument. (i.e. Tooling bars, theodolites, levels, tilt sensors, dihedral reference mirrors, etc.)**	**Optical Branch Support**
I&T Ground Support Equipment (I&T GSE)	Assist in execution of I&T (i.e. Oscilloscopes, meters, current probes, break out boxes, ESD protective equipment, IT equipment, etc.)	I&T

NOTE: Substantial amounts of GSE are required to support the integration effort. Much of this equipment will be developed and used at the subsystem level and be delivered with the flight hardware to I&T. Other equipment will be developed specifically for I&T use. Only GSE identified in this table as being provided by I&T is included in the I&T costs. The costs for all other GSE are assumed to be carried by the group identified in the column marked “Provider.” The costs and development schedule of this equipment is not trivial. This list is not meant to be exhaustive or complete.

GSE Required for I&T effort, Ct'd

Equipment	Purpose	Provider
Command and Data Handling (C&DH) GSE	**Test and checkout the C&DH subsystem. (i.e. Timing GSE, bus monitor etc.)**	**C&DH Subsystem**
Propulsion GSE	**Testing and integrating the propulsion subsystem (i.e. propulsion system monitoring EGSE, pyro load simulator/tester, pressurization rack, propulsion system MGSE: dolly and lifting slings etc.)**	**Propulsion Subsystem (with assistance from Electrical and Mechanical)**
Deployment Ground Support Equipment (DGSE)	**Test the S/C deployment systems, Solar Array and High Gain antennas, sun shield, other covers. (i.e. G-negation systems, etc.)**	**Deployment Subsystems (with assistance from Mechanical Subsystem)**
Attitude Control System (ACS) GSE	**Stimulate and test the ACS. (i.e. Goddard Dynamic Simulator, Sun Sensor Stims, Star Tracker Stims etc.)**	**ACS Subsystem**
RF GSE	**Test the S-band and Ka-band RF Receivers and Transmitters & links (i.e. RF test racks, hat couplers, receivers, demodulators, cable & couplers etc.)**	**RF Subsystem**
Instrument Ground Support Equipment (IGSE)	**Test, stimulate, and handle the instruments during stand alone testing, and integrated testing (Command and Telemetry computers, calibration sources, MGSE, purge systems, protective covers etc.)**	**Instrument Providers**
Contamination GSE	**Monitoring and control of contamination & sources (i.e. cleanroom garb, wipes, inspection lights, vacuums, chemicals etc.)**	**Contamination Engineering**

SM Integration – Propulsion Considerations

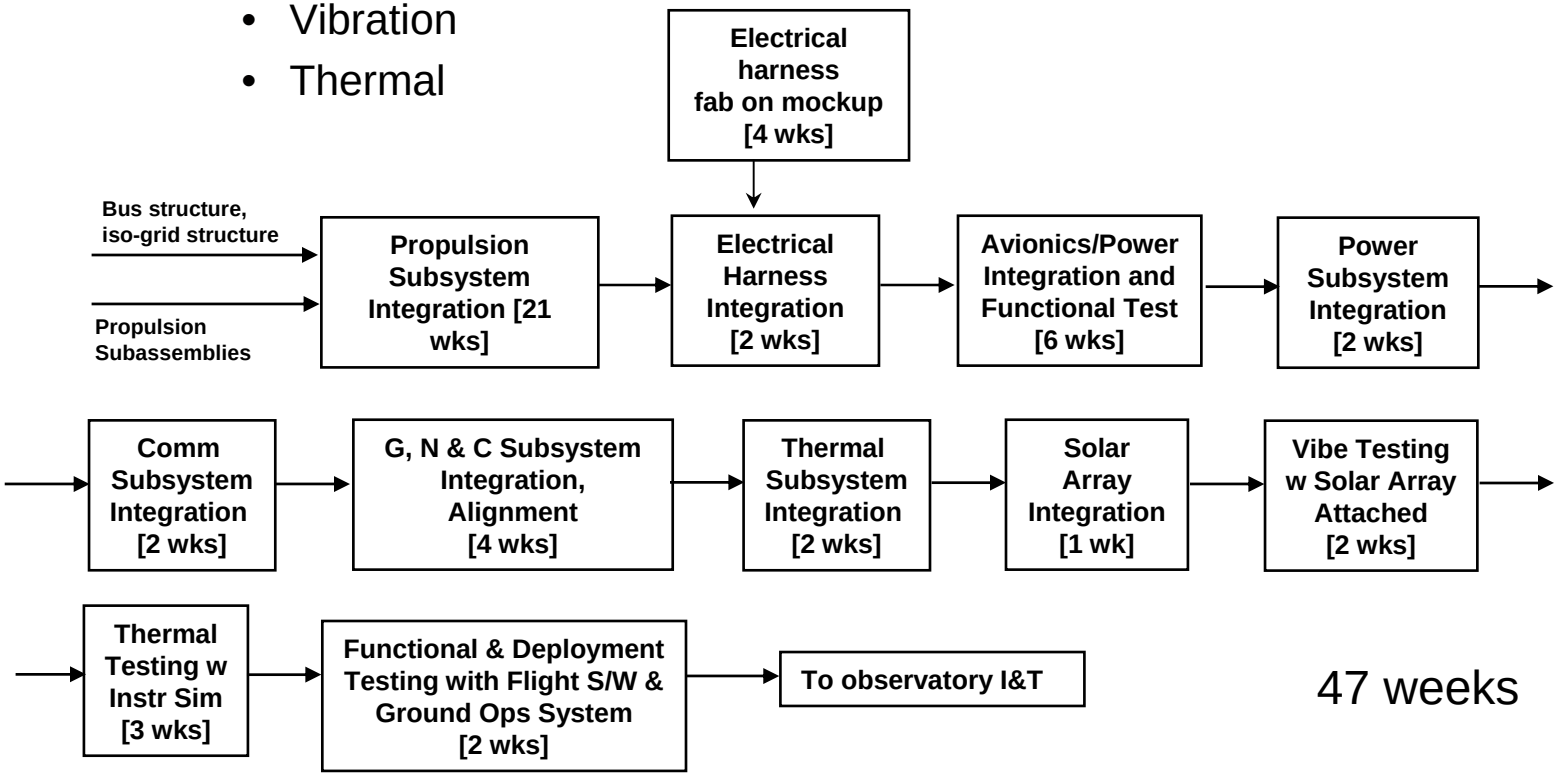
- The IXO propulsion system is not modular (no separate propulsion module)
  - IXO propulsion is highly integrated to the S/C Bus and Isogrid, with many propulsion interconnections between the two.
    - Propulsion integration should not begin until S/C Bus and metering structure are mated
- Significant time for welding and X-ray inspection are required, which are hazardous to flight electronics and personnel
- Only propulsion mechanical and electrical integration, propulsion thermal, and possibly SM thermal installations can go on in parallel.
- Requires 21 weeks to complete [ref., MDL Propulsion final report]*
  - 5 days per week
  - Welding during regular hours, inspection on off-shift
  - Must be ‘up front’, before avionics are installed

List of Large Thermal/Vac Chambers in the US

- There are five thermal/vac chambers in the US that are large enough to accommodate the fully extended Con-X spacecraft (which is approximately 12' in diameter by 75' high):
  - Arnold Engineering Development Center, Arnold AFB, Tullahoma, Tennessee; 42' diameter by 82' high (vertical)
  - NASA JPL, Pasadena, California; 27' diameter by 85' high (vertical)
  - NASA JSC, Houston, Texas; 65' diameter by 120' high (vertical)
  - NASA GRC, Plum Brook Station, Sandusky, Ohio; 100' diameter by 122' high (vertical)
  - Lockheed Martin Missiles and Space, Sunnyvale, California; 40' diameter by 80' long (horizontal)
- There are a number of chambers in the US which could accommodate the IXO partially extended

S/C Module Integration & Test – Top-Level Flow

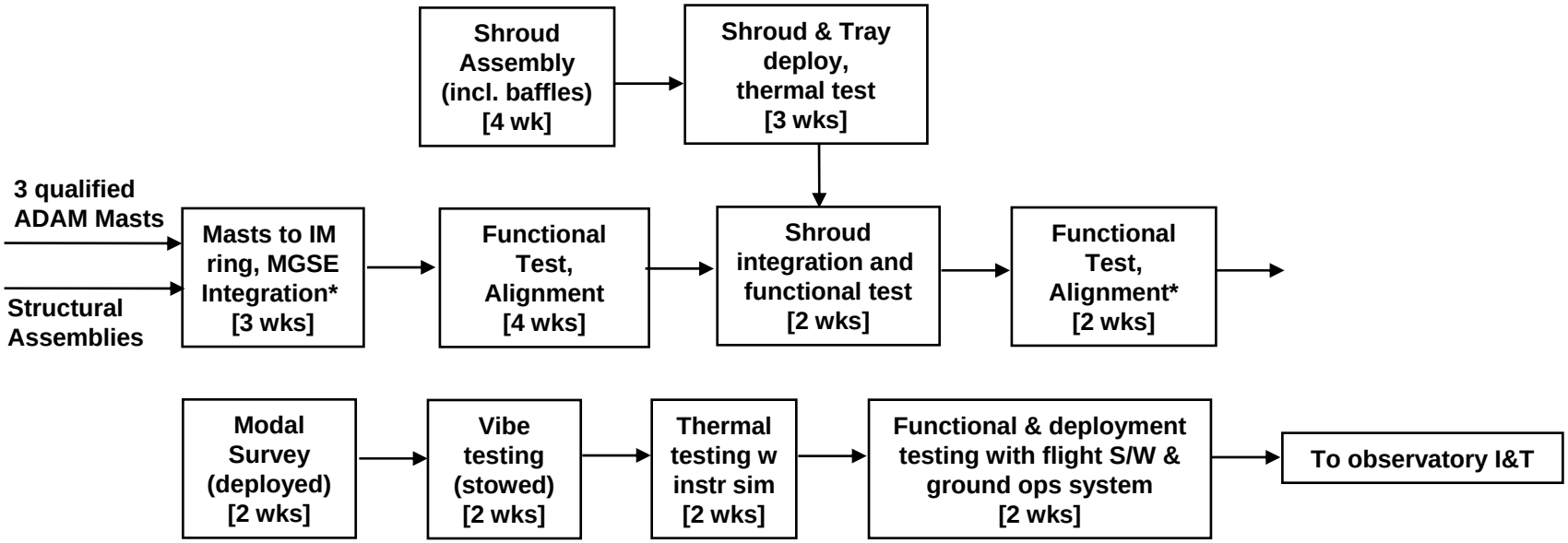
- Assumptions
  - Structure Strength qualified
  - All boxes environmentally qualified
    - EMI/EMC
    - Vibration
    - Thermal



47 weeks

Deployment Module I&T – Top-Level Flow

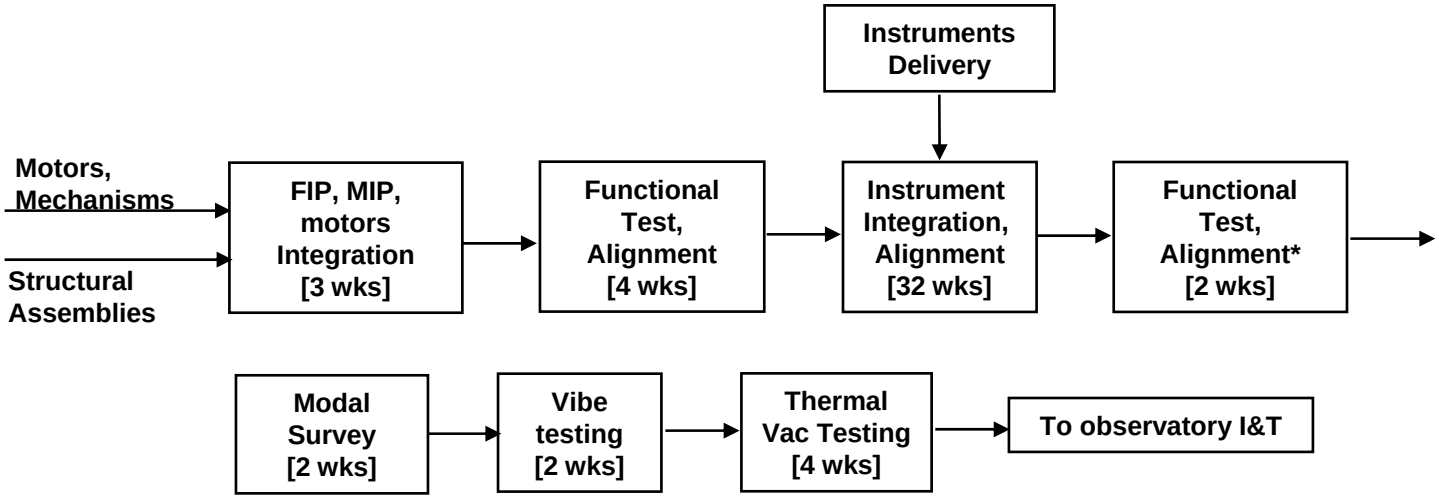
- Assumptions
  - ADAMS Masts, Shroud & trays environmentally qualified.
  - Structure Strength qualified
  - All boxes environmentally qualified
    - EMI/EMC
    - Vibration
    - Thermal



20 weeks

Instrument Module I&T – Top-Level Flow

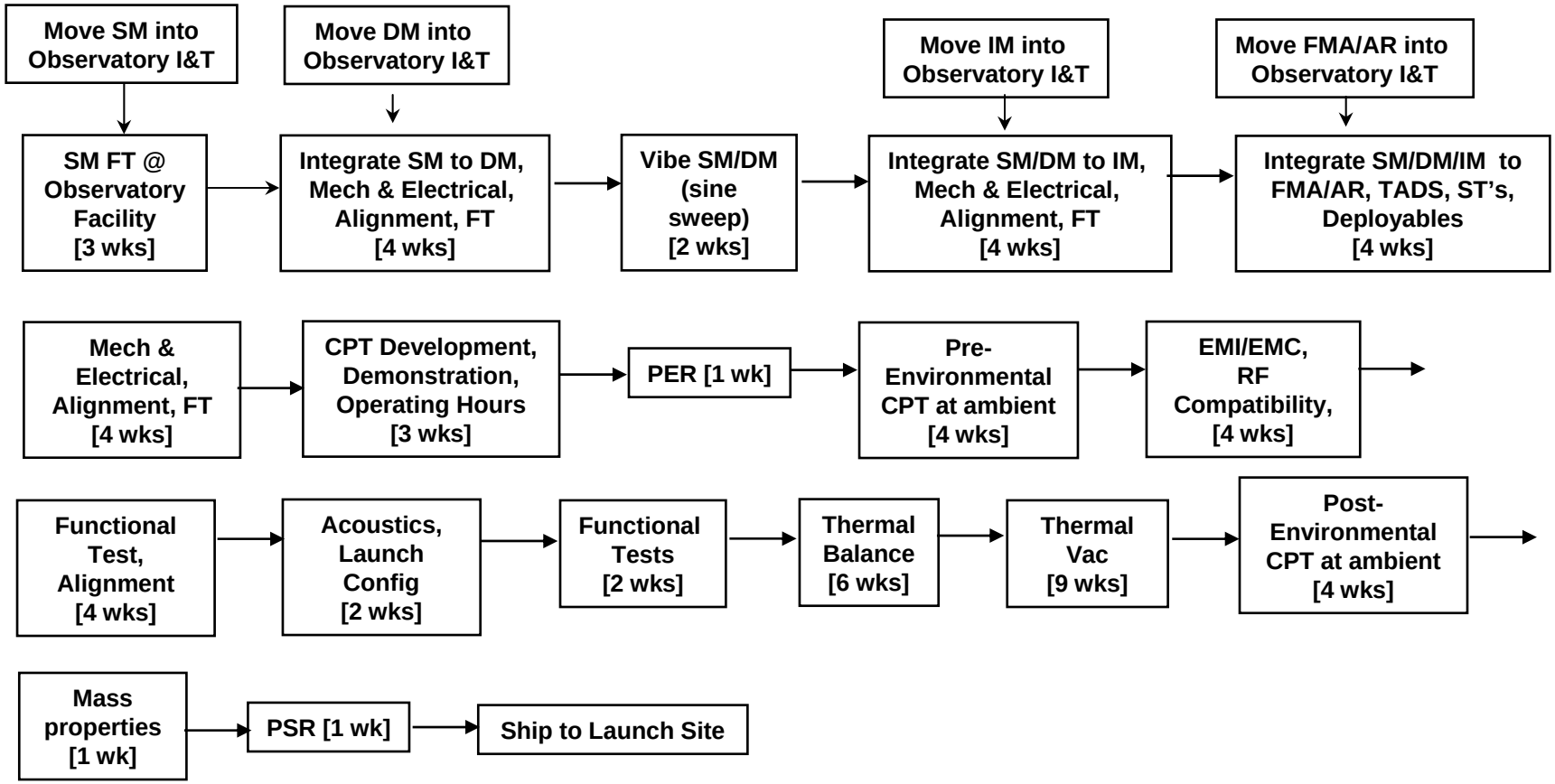
- Assumptions
  - Instruments environmentally qualified.
  - Structure Strength qualified
  - All boxes environmentally qualified
    - EMI/EMC
    - Vibration
    - Thermal



25 weeks

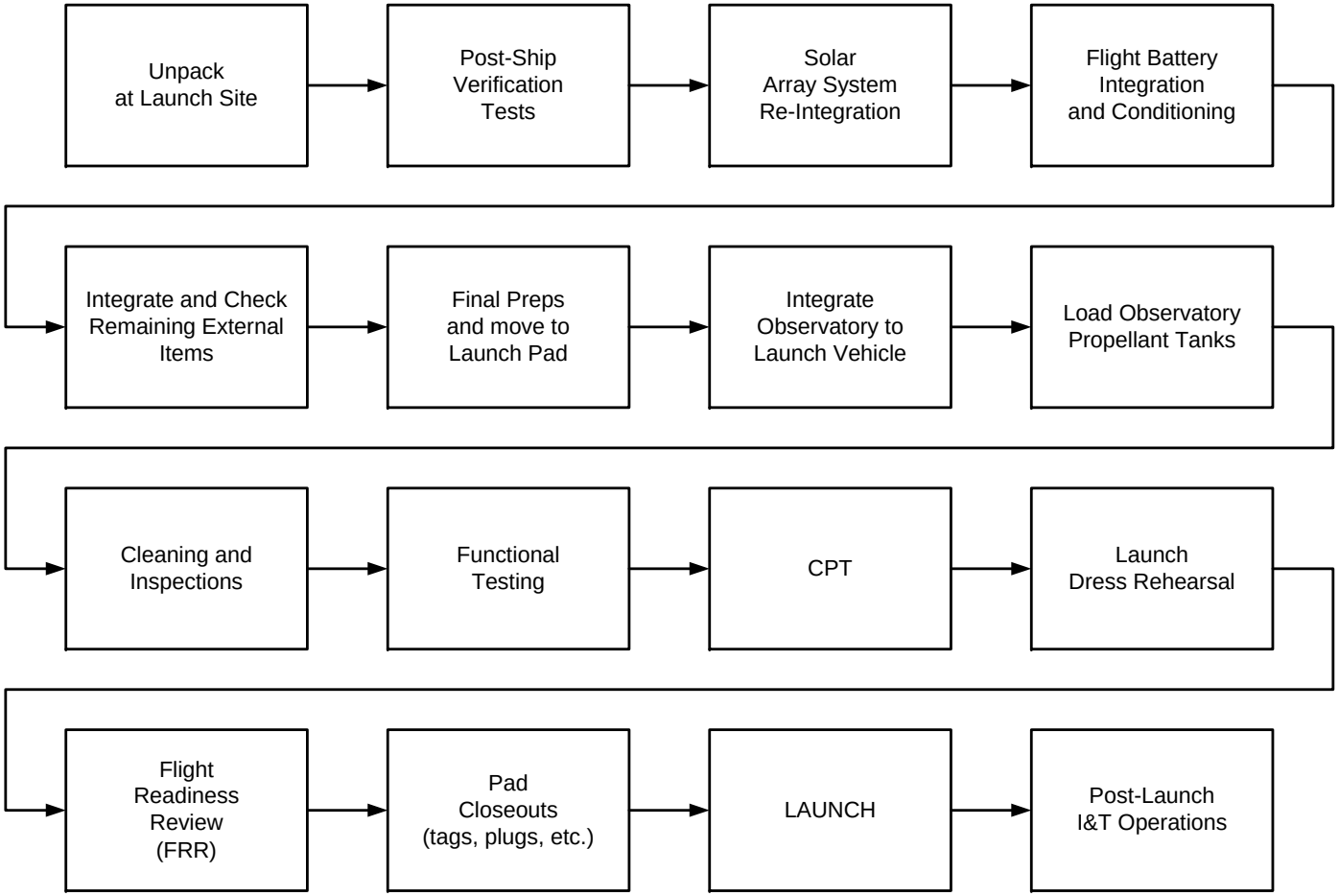
Observatory I&T – Top-Level Flow

- Assumptions
  - All Modules arrive fully qualified

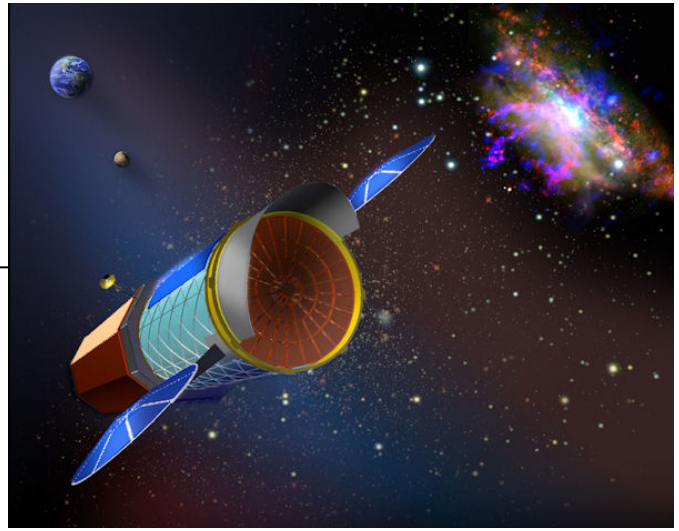


62 weeks

Launch Site Ops



IXO Mission Operations



Jay Bookbinder

Harvard-Smithsonian Center for Astrophysics

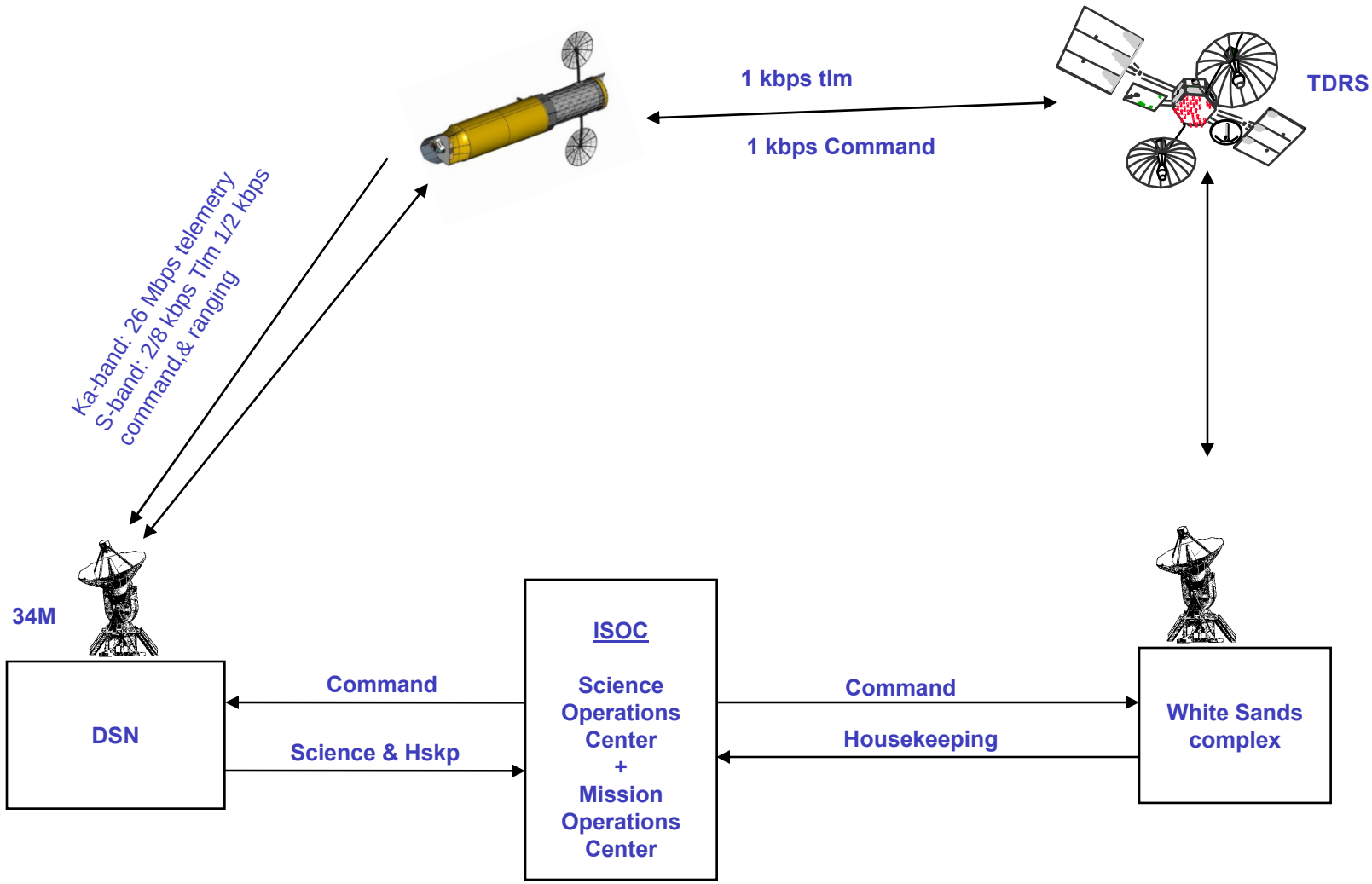
March 12, 2009

Mission Operations Overview

- IXO will be a facility class observatory:
  - Programs selected via competitive Peer Review
- IXO operates as a queue-scheduled observatory:
  - Pointing at selected targets in the most time efficient way consistent with science and observatory constraints
  - No unusual mission or operational constraints
  - No unusual communication requirements
- Time on a target (pointings):
  - 10^3 to 10^6 sec; observations may have several pointing intervals
  - 1 – 20 observations per week
- IXO Operations Concept is well developed:
  - Based on the Chandra model
  - Re-use of existing expertise and facilities
- IXO MODA follows recommendations from the "Portals" NRC report

Panoramic view of the Chandra Operations Center

IXO Mission Operations Architecture



Driving Requirements for MO&DA - I

Parameter	Requirement	Source/Rationale	Performance
Telescope pointing (aspect) determination ground-based post processed	1 arcsec, 3σ	Flow down from aspect determination error budget to meet the celestial location knowledge.	Derived star tracker attitude knowledge requirements is 0.5 arcsec, 3σ. Pointing budget supports achieving requirement
Telemetry Volume	Capable of downlinking 1 day of data per pass; 1 hour per pass	Flow down from Ops Concept, in conjunction with onboard storage limit	Ka-band antennas and ground stations sized to meet requirements with link margin (221 kbps daily avg)
Downlink Frequency	1 downlink/day	Ops Concept: joint requirement on sizing of on-board storage	1 downlink/day
Timing	Arrival time accuracy of ±100 microseconds (UTC)	Top level requirement	Arrival time accuracy ±90 μsec
Mission Duration	5 years normal science operations	Top level requirement	Systems designed to meet requirements
Observing Efficiency	85%	Science Traceability Matrix to achieve all goals	L2 orbit meets
Sky Coverage	90% 2x/year, 100% 1x/year	Top level requirement	L2 orbit meets

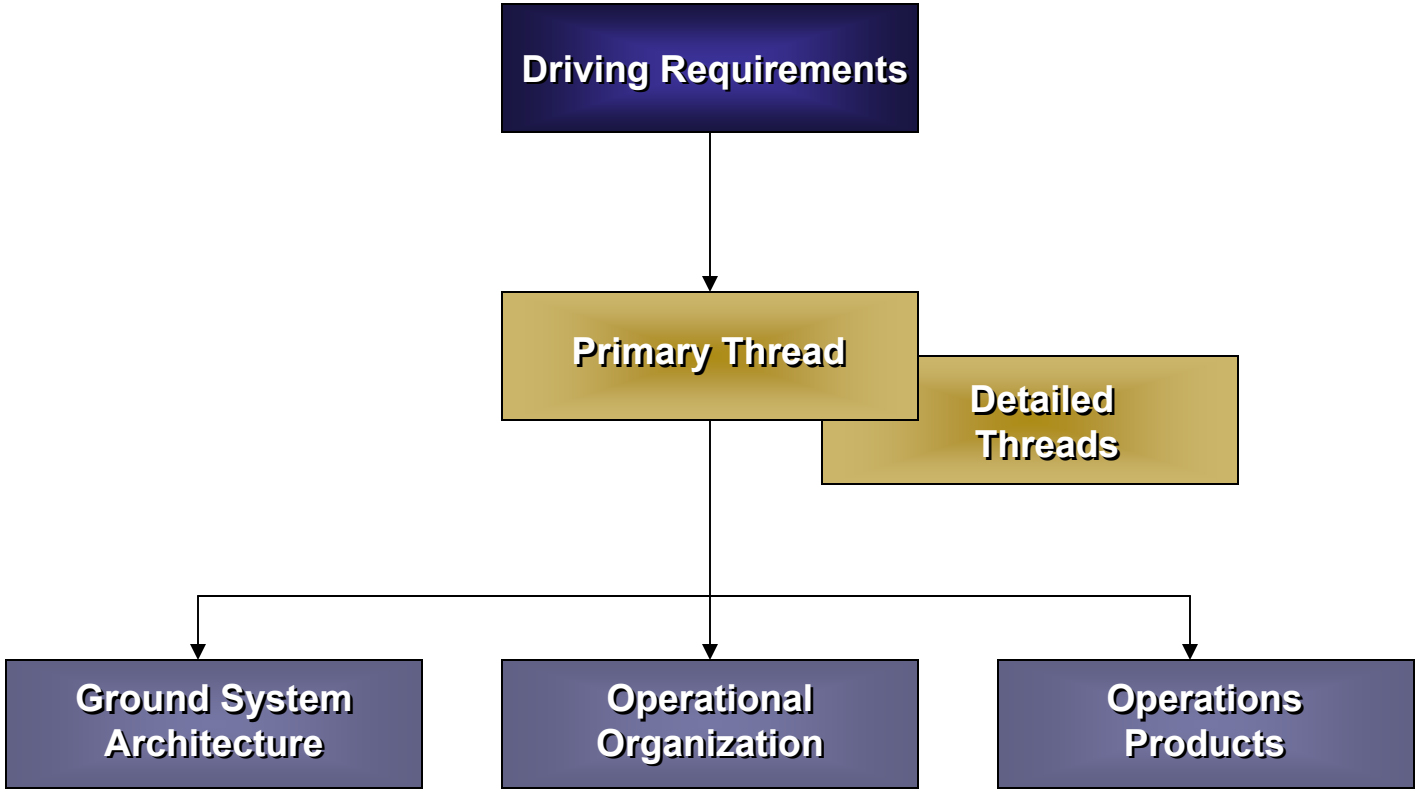
Driving Requirements for MO&DA - II

Parameter	Requirement	Source/Rationale	Performance
Data Uplink Volume	4 Mbs	Ops Concept	S-band uplink meets.
Data Uplink Frequency	Once/week	Ops Concept	Science Observing Plan generated and uplinked weekly
Data Latency	2 weeks (72-hour goal) from completion of observation to product delivery*	Top level requirement	Ground system requirement meets requirement. Should achieve 48 hours.
TOO Frequency	Approx. 2x per month	Top level requirement	Design can exceed requirement
TOO Response Time	<24 hours	Top level requirement	
Archive Storage	10 years of all raw and processed (to Level 3) mission data, plus reprocessing	Derived from mission lifetime rqmnt	Ground system design meets requirement

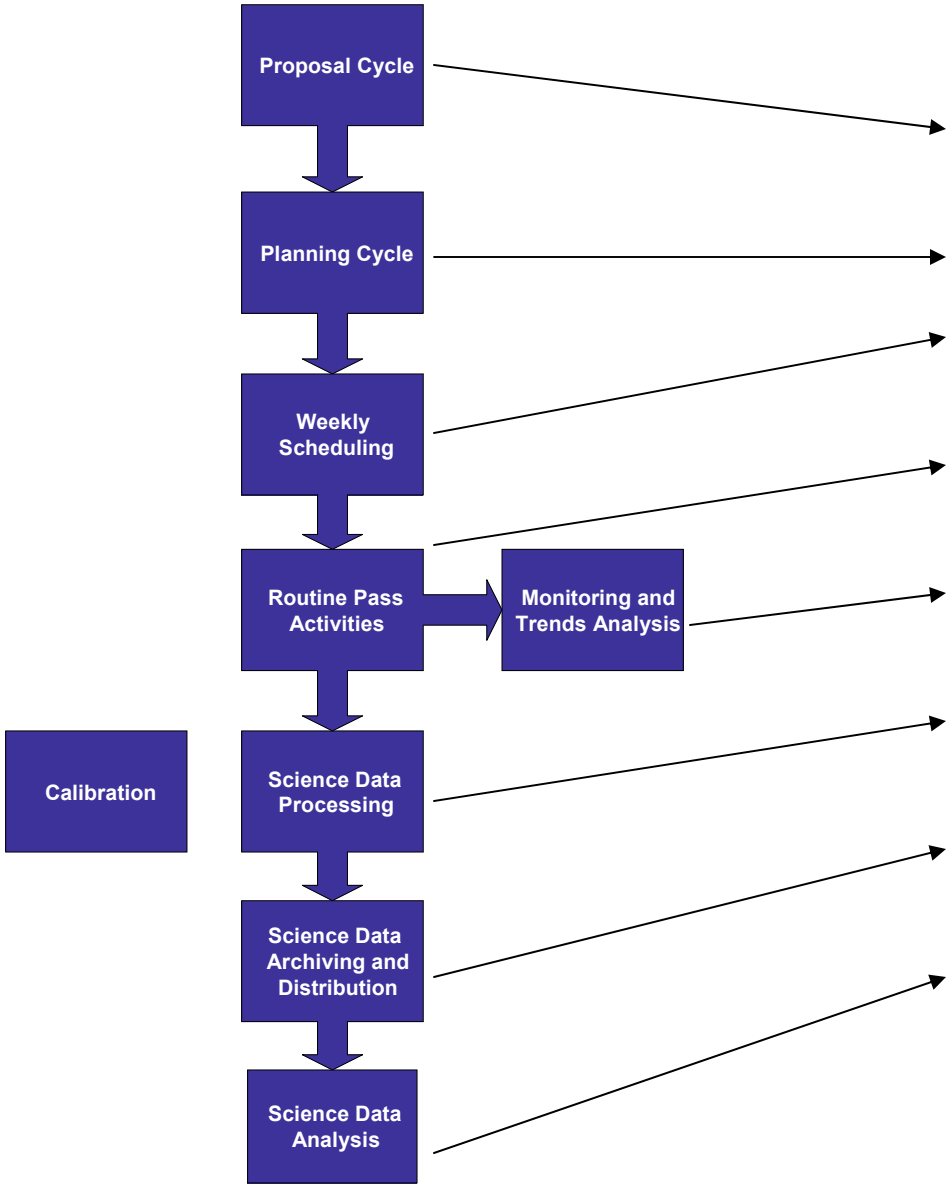
Excludes bright source observations

IXO Operations Concept

- Significant progress has been made in identifying and documenting the IXO operations concept. The Operations Concept document formed the basis for the MO&DA components of IXO and is based on Chandra's Operations and Concept.

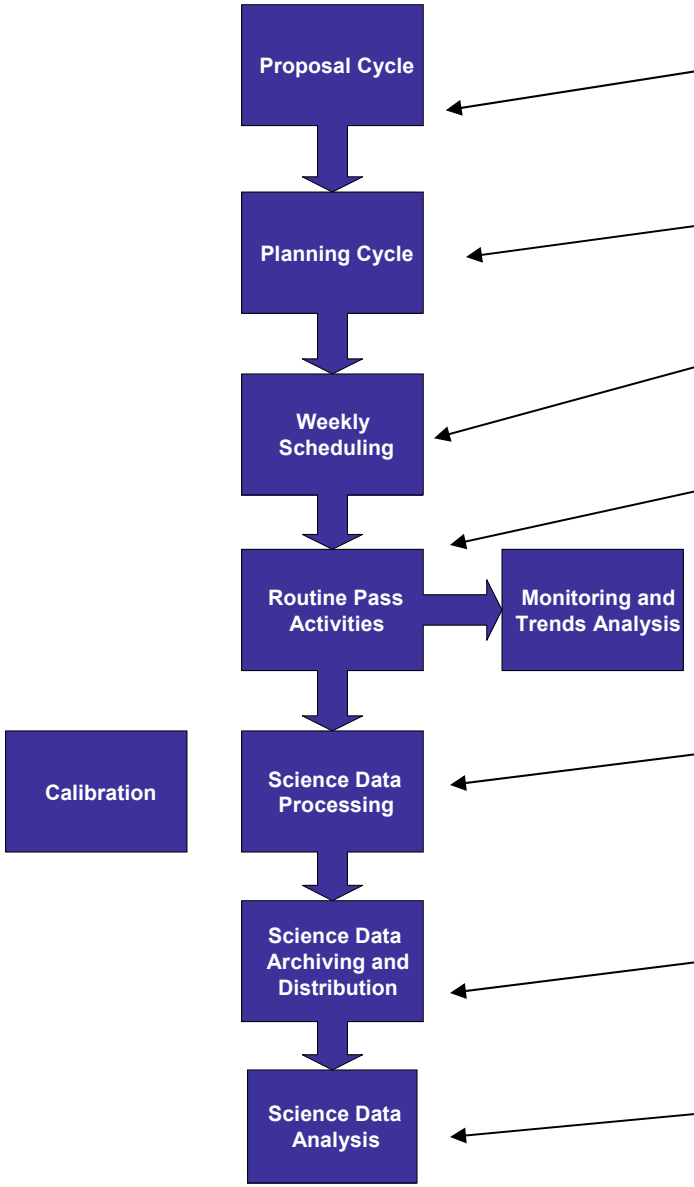


Primary Operational Thread



- Observer prepares and submits proposal
- Generate long-term science plan
- Flight mission planning cycle, generate command loads
- Uplink, tracking, on-board activities, downlink
- Engineering and Science Instrument monitoring and analysis
- Level 0 to 3
- Science Archiving, data distribution, web access
- Analysis tools, documentation, cook-book recipes

Primary Operational Thread and Driving Requirements



- Mission Duration
- Observing Efficiency
- Sky Coverage

- Observing Efficiency
- Sky Coverage
- TOO Frequency
- Calibration requirements

- Uplink Frequency
- TOO Frequency
- TOO Response Time

- Downlink Frequency
- Telemetry Volume
- Timing
- Uplink Frequency
- Uplink Volume
- TOO Response Time
- Data Latency

- Telescope Pointing
- Telemetry Volume
- Timing
- Data Latency
- Archive Storage

- Mission Duration
- Telemetry Volume
- Data Latency
- Archive Storage

- Telescope Pointing
- Sky Coverage
- Timing

Detailed Operational Threads

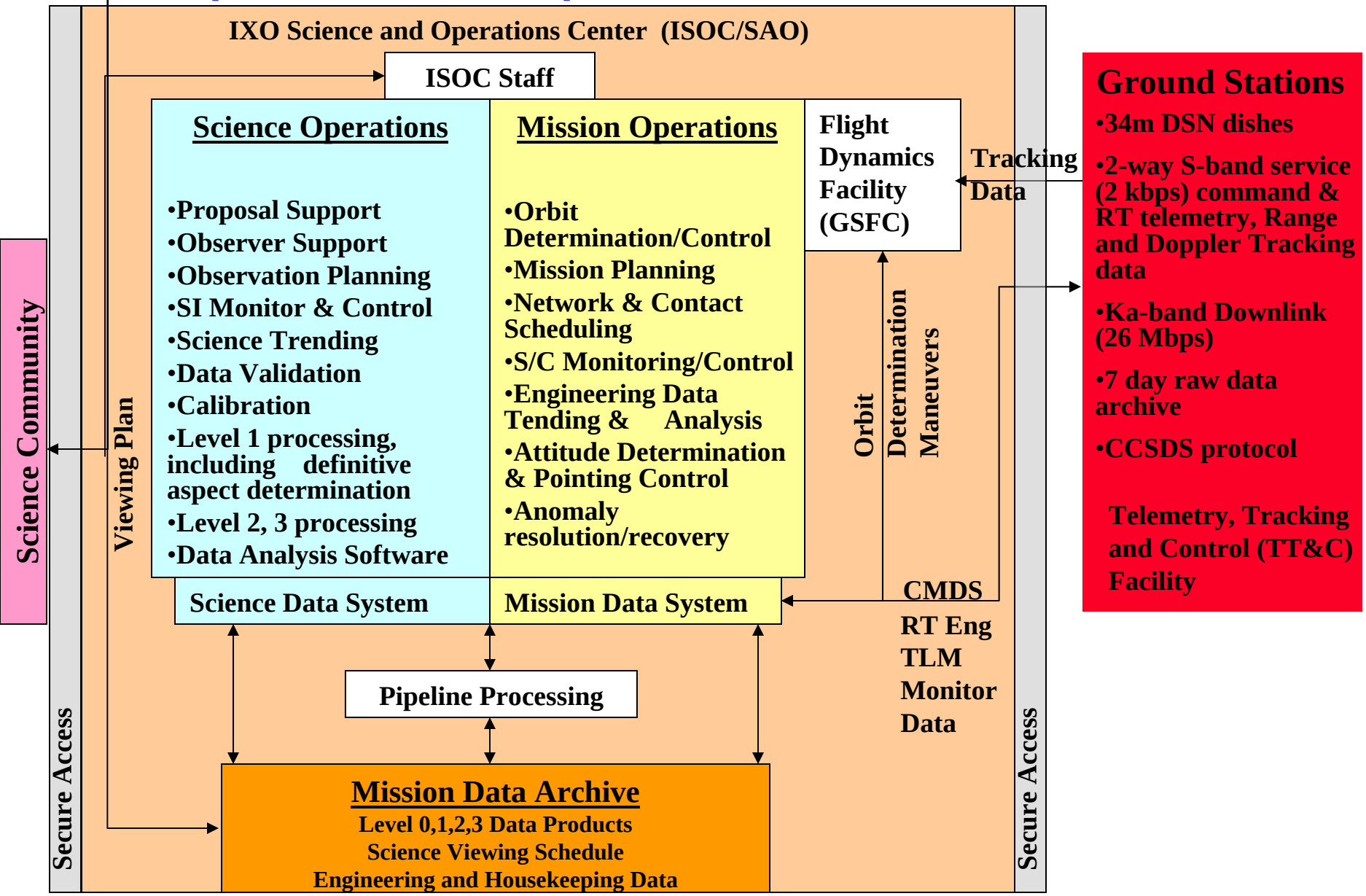
5.1	Peer Review
5.2	Science Planning and Scheduling
5.3	Contact Planning and Scheduling
5.4	**Station Management**
5.5	On-Board Recorder Management
5.6	Momentum Management
5.7	High-Gain Antenna Management
5.8	**Routine Pass Activities**
5.9	Spacecraft Health and Safety Monitoring
5.10	Instrument Performance Monitoring
5.11	Trending
5.12	Time Management
5.13	Orbit Determination
5.14	Science Data Processing
5.15	Science Data Archiving and Distribution
5.16	Science Data Analysis
5.17	Calibration
5.18	Calorimeter Recharge
5.19	Target of Opportunity
5.20	Flight Software Maintenance
5.21	**Reduced Aperture Operations**
5.22	Radiation Operations
5.23	Anomalies

ISOC – a Flagship Mission Class Science Center

ISOC Key Functions and Services

- **Phase CD:**
  - Develop observatory calibration plan including optics, instruments.
  - Support execution of the calibration activities by the optics and instrument teams
  - Supports instrument and observatory I&T
  - Develop science planning and flight planning s/w
  - Pre-launch data flow development, science analysis software development, etc…
- **Phase E:**
  - Flight operations support
  - Instrument operations and calibration
  - Data V&V
  - Data analysis
  - Distribution and archiving of data and data products
  - Help desk and user support services
  - Proposal submission processing and peer review evaluations
  - Software development and documentation for science analysis
  - Scientific research
  - Grants management and administration
  - Education and public outreach

IXO Operations Concept Reference Architecture



Mission Data System

The Mission Data System (MDS) performs all traditional mission data processing functions for the spacecraft platforms and for science instrument health and safety. The MDS consists of the data system resources required for:

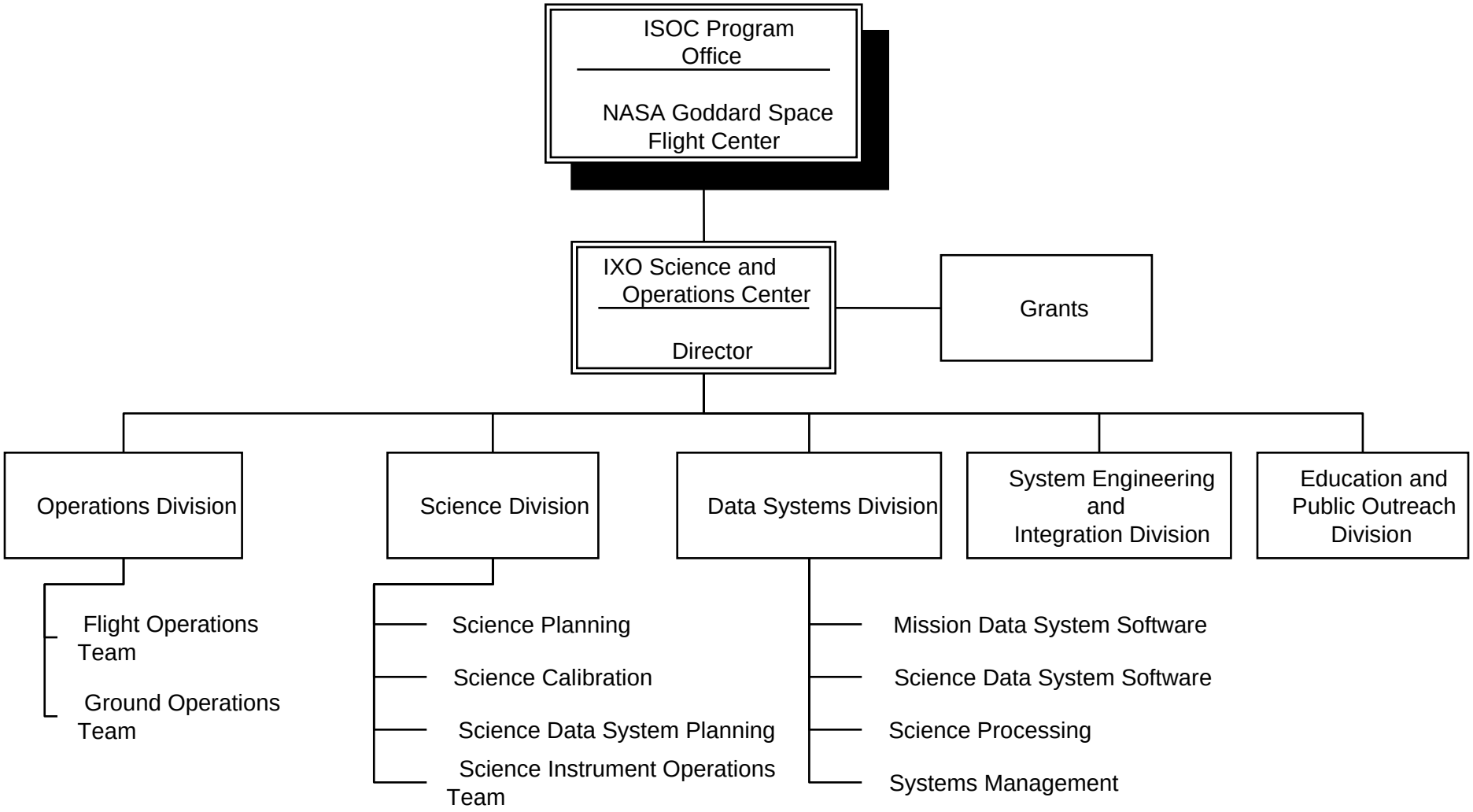
- Commanding the spacecraft
- Real-time health and safety monitoring of spacecraft and science instrument engineering data
- Observatory and science instrument scheduling
- Scheduling tracking support
- Power management
- Thermal management
- Orbit and attitude verification
- GN&C file management
- Receipt & processing of telemetry data

Science Data System

The Science Data System (SDS) consists of the data system processing, storage, and long term archiving resources required for:

- Science data processing (e.g. pipeline processing of these data using algorithms provided by the SIOT)
- Management of and accountability for all data (telemetry, ancillary, and products)
- Distribution of these data as requested by the observer, ISOC staff, and SI teams
- Building and distributing the software necessary to analyze the observation data
- Dissemination of public data

Operational Organization – Post Launch



ISOC Staffing

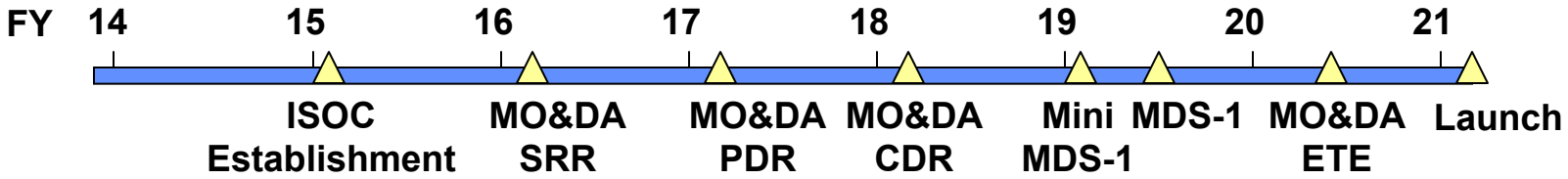
- ISOC will be staffed around the clock to support initial s/c and instrument checkout
  - – gradually reduced over first 100 days to normal operations staffing levels
- During normal operations ISOC expected to be staffed 8 hours per day/5 days per week for normal operations
- Staff will be on call in the event of a safety alert from the observatory
- Staff will be on call 24/7 to review and implement TOOs.

Special Operations

- Launch and Early Operations
  - Increased staffing at ISOC
  - Increased ground station contacts –
  - TDRSS used to monitor critical events
  - Outgassing
  - Spacecraft checkout, instrument checkout
  - Nominal operations being following insertion into L2 orbit
- Orbit insertion maneuvers
- Station-keeping (every 21 days)
- Software loads
- Radiation operations
- Anomaly and Safe Mode Recovery
  - Observatory notifies ISOC via standard downlink
- TOO – are considered as part of normal operations

Transition from Chandra to IXO

- **The IXO Science and Operations Center (ISOC) will evolve from and be co-located with the Chandra X-ray Center at SAO:**
  - Chandra Control Center data system is designed as multi-mission with modular interfaces to command and telemetry and other data bases
  - IXO transition through addition of new strings of hardware to existing facility in Cambridge, MA and building on existing teams and procedures
  - IXO Science Data System architecture functionally similar to Chandra Science Center Data System: planning tools, pipeline processing, archive, monitoring and trends, calibration tools, analysis system
- **Key differences identified and scoped:**
  - Potential contributions to Mission Operations by ESA, JAXA
  - L2 orbit: simplified mission planning without radiation belts, well understood station-keeping
  - Impact of additonal instruments:
    - Science processing of additional instrument data sets
    - Calibration support
    - User support
    - Analysis tool emphasis on spectroscopy: development phased to support Science Instrument Development
    - Analysis tool emphasis on polarization: development phased to support Science Instrument Development



Operations Metrics

During the science operations phase data supporting the following [+ TBD] metrics will be gathered and reported as an early indication of potential problems and as a measure of operations management effectiveness.

- Observing efficiency
- Data loss statistics
- Fuel remaining and other consumables
- Data delivery effectiveness
- Help desk statistics
- Grant award efficiency

IXO Operations Concept Document

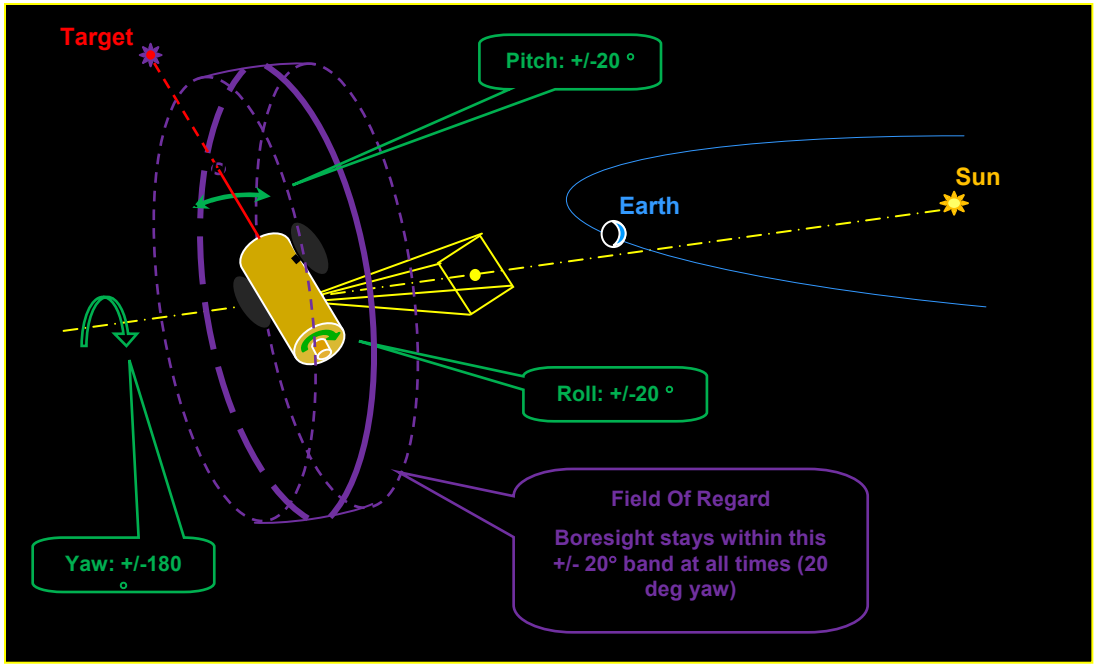
- Under initial review
- Based on Constellation-X draft which was based on the CXC approach.

BACKUP Material

Communications

- **Early operations:**
  - Near-continuous tracking (range & doppler) required for first 48 hours to plan for and reconstruct dispersion correction maneuver (planned for L+24 hours)
- **Normal operation:**
  - 30 minutes of ranging and doppler every day
  - Alternating northern and southern hemisphere station contacts
  - This scenario requires the spacecraft to limit its momentum unloads to no more often than once every two days
- **Also see RFcomm section**

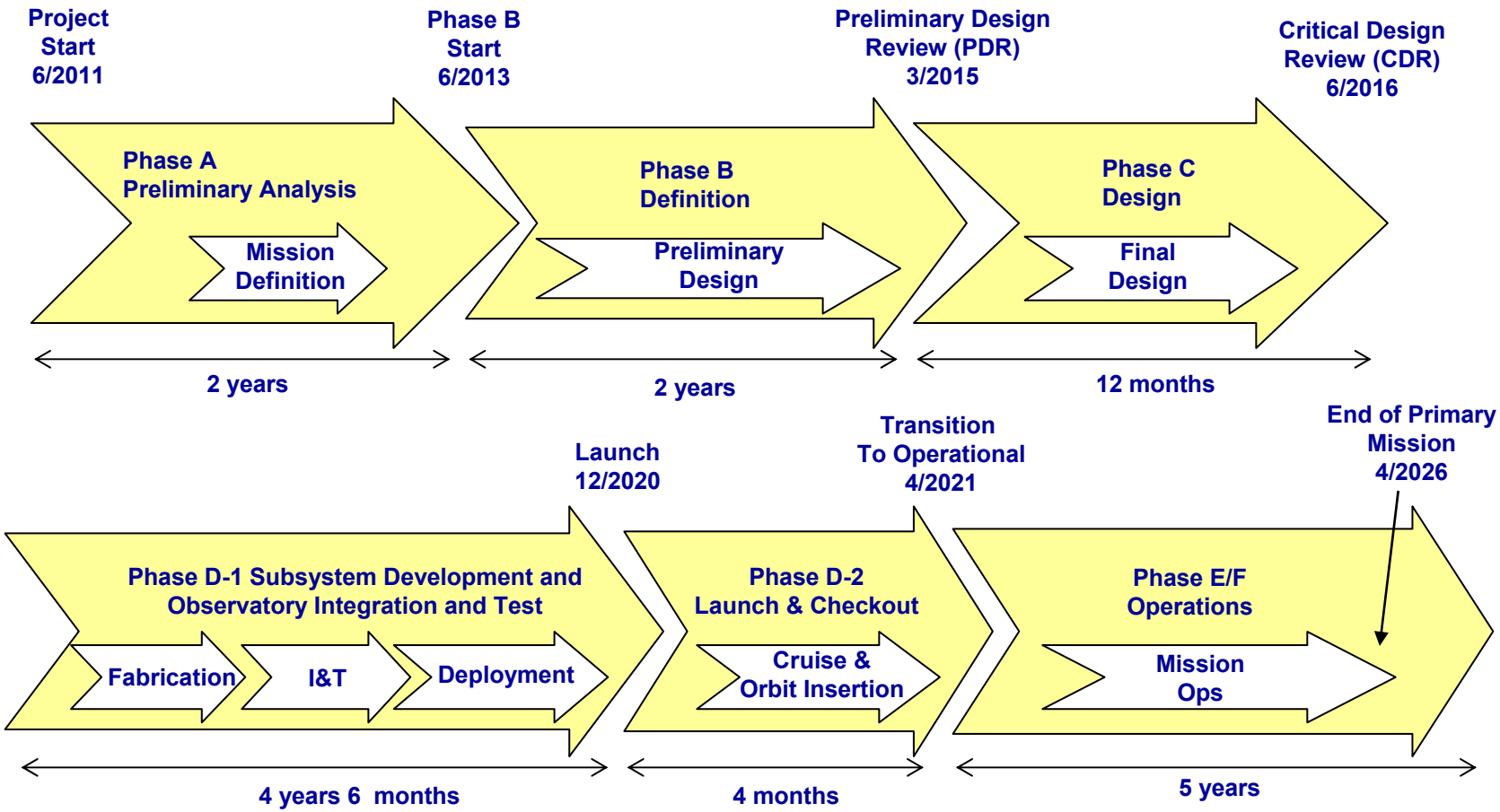
Field of Regard



Science Operational Modes

		Science Modes			
		Mode 1	Mode 2	Mode 3	Mode 4
Instrument Operations	Science	XMS/CIS, XGS	WFI, HXI, XGS	X-Pol, XGS	HTRS, XGS
	Standby	WFI, HXI, X-Pol, HTRS	XMS/CIS, X-Pol, HTRS	WFI, HXI, HTRS,XMS/CIS	WFI, HXI, XMS/CIS, X-Pol
Observation Duration (hours)	Average	10 hours			
	Minimum	30 minutes			
	Peak	48 hours			
Percent time for each Mode		40%	40%	10%	10%

IXO Schedule



Targets of Opportunity (TOO)

- Generally, an observation of a short term phenomenon discovered by another observatory that is interesting enough to interrupt planned IXO observations
- Determination made by project scientist (or designee)
- Observation will begin within 24 hours of determination
- Frequency expected to be ~ 2x/month
- Requires additional observing plan upload, re-plan of near-term observatory schedule

Data Release Policies

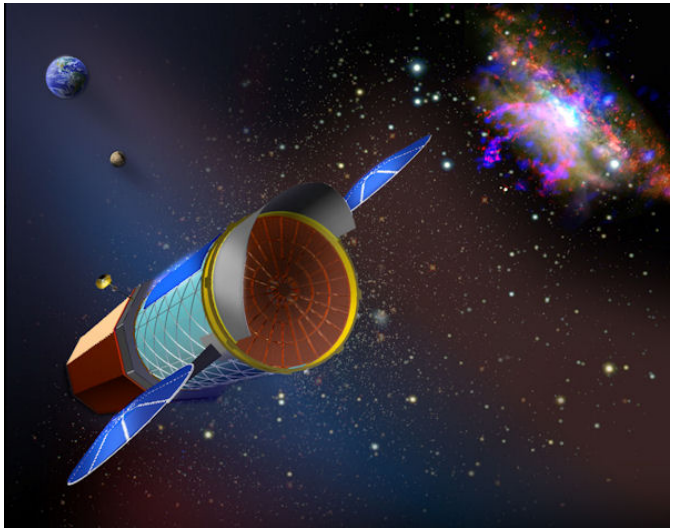
GO policy: 1 year proprietary

GTO policy: TBD

Calibration data policy: public unless part of a GO/GTO observation.

IXO Table Top Review

2009 03 12
NASA GSFC, Bldg 23, Room C130D

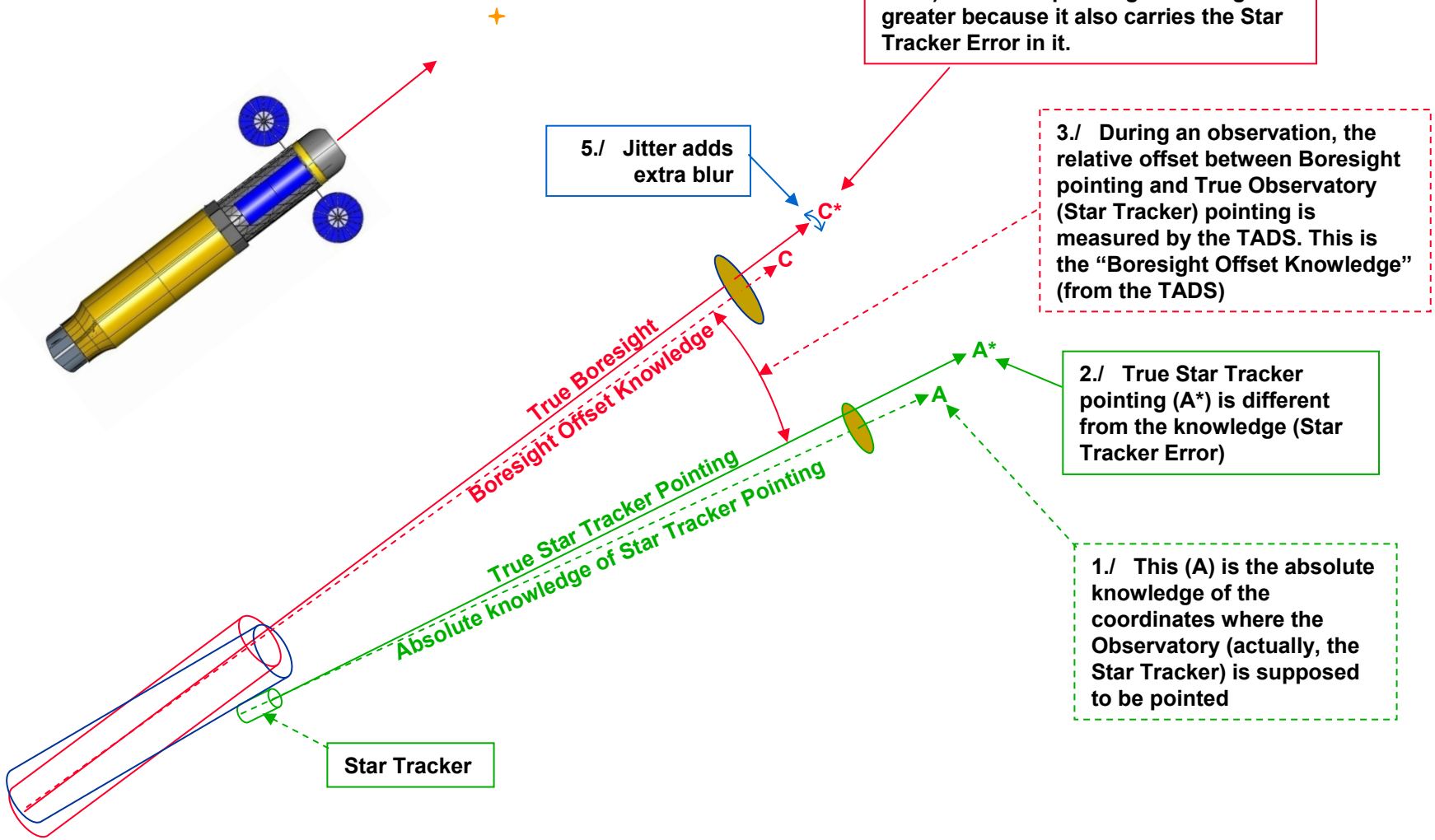


Subsystems Overview

Gabe Karpati
IXO Mission Systems Engineer

GN&C

Observatory Level Pointing Basics



True Boresight is defined as the line connecting the "Center Pixel" on the XMS/WFI to the FMA node.

Observatory Level Pointing Performance Summary

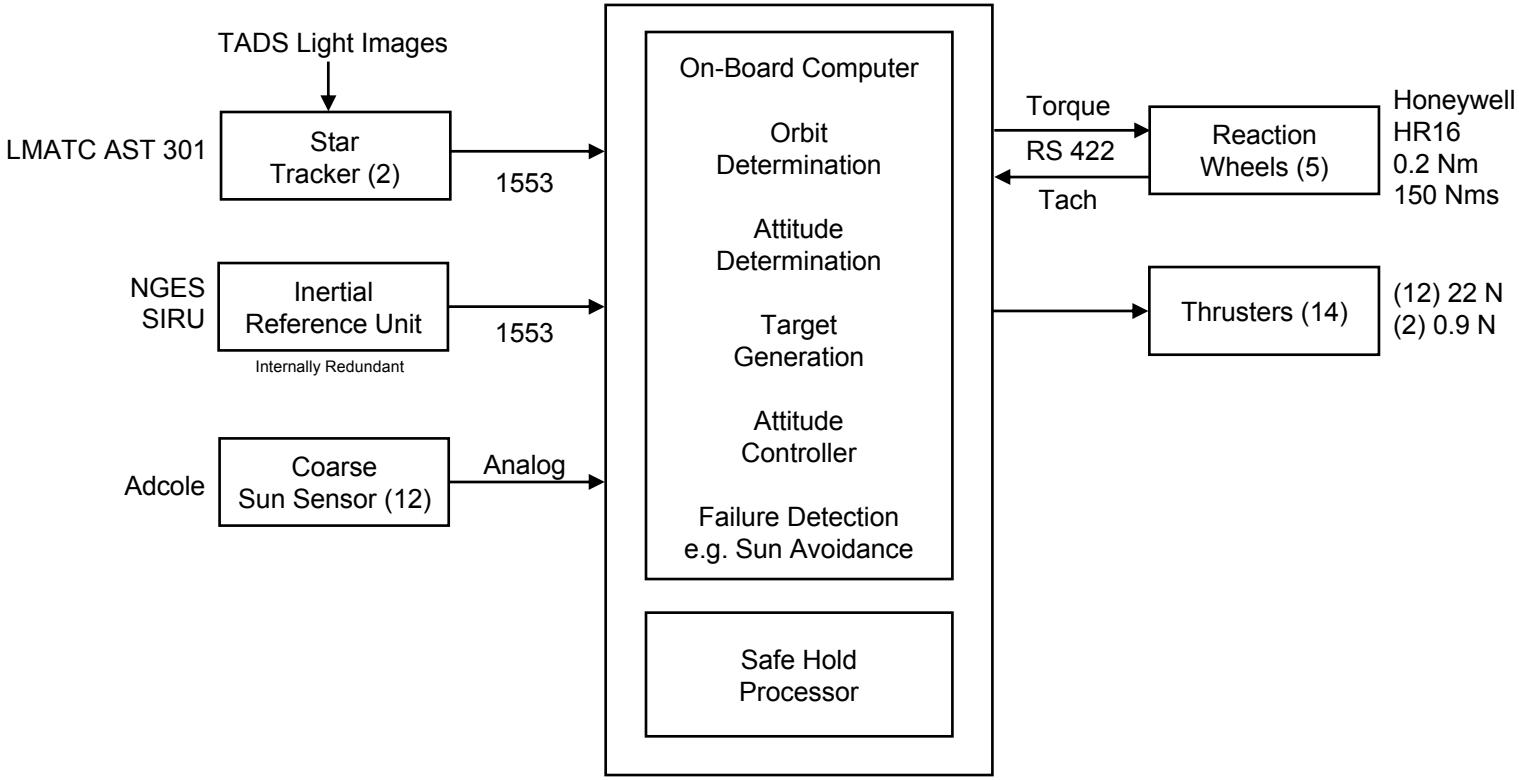
Term	Definition	Requirement	Predicted Performance	Stat
Image Position Reconstruction Knowledge (a.k.a.: "Aspect Reconstruction)	The absolute knowledge of an image's position relative to the Truth:	• Radial: 1 arcsec (that is Pitch and Yaw combined, equivalent to ~0.7" pitch and ~0.7" roll) • Roll: 3 arcsec	• Radial: .54 arcsec • Roll: 2 arcsec (stability over a science observation)	HPD
Image Position Control	The absolute precision of placing and keeping an image on the Focal Plane Detector	• Pitch and Yaw: 10 arcsec • Roll: 30 arcsec	▪ Pitch and Yaw: 1.54 arcsec • Roll: < 10 arcsec	3σ
Defocus	Abs. max. FMA Node to Detector distance variation without correction by any focus mechanism	• +/- 0.3 mm	▪ +/- 0.16 mm	3σ
Lateral Translations	Boresight Misalignments Relative to FMA Optical Axis due to Metering Structure translations	▪ +/- 1.6 mm (16 arcmin)	▪ +/- 1.2 mm (12 arcmin)	3σ
Jitter (excluded from the Image Position Knowledge requirements)	Jitter effects encompass all high frequency errors above the bandwidth of the Control System and Monitoring System	▪ 200 milliarcsec over 200 msec	▪ 20 milliarcsec abs. worst case over any period msec By Reaction Wheel momentum management in a 5 RW configuration, a steady state jitter of .2 milliarcsec is achievable	HPD

Note: one mm corresponds to ~10" (or 1 " to 100 um) at 20m

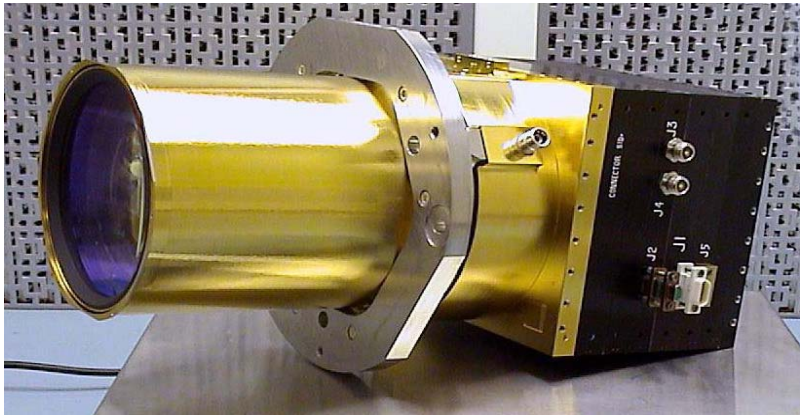
ACS Overview

- Three-axis stabilized, inertial pointing
  - X axis points to Sun, Z axis points to science target
  - Solar panels pointing towards sun maintained for all modes: Science, slew, maneuver, safe hold, and cruise
- Two AST 301 Star Trackers
  - Coaligned with telescope boresight to provide precision attitude knowledge
  - Also used as part of the Telescope Aspect Detection System (TADS)
- IRU mounted on S/C Bus
  - Internally redundant
- Five reaction wheels arranged in a JWST-like "L-infinite configuration to maximize momentum, biased for a 4:1 or greater ratio between the X/Y axis and the Z axis
  - RWL Torque Capability per Axis: 0.2 Nm (conservative)
  - Slews require authority mainly in the X axis
  - Momentum accumulation primarily in the Y axis
- Nearly continuous low disturbance thruster based solar torque unloading allows uninterrupted science observations
- Mass Properties
  - Ixx = 320,000 kgm^2
  - Iyy = 320,000 kgm^2
  - Izz = 12,000 kgm^2
- Digital Control (PID) with 0.02 Hz Bandwidth
  - Uses Star Tracker Exclusively (gets better with Gyro, e.g. SIRU)

ACS Block Diagram



Spitzer's AST-301 Star Tracker (by LMATC)



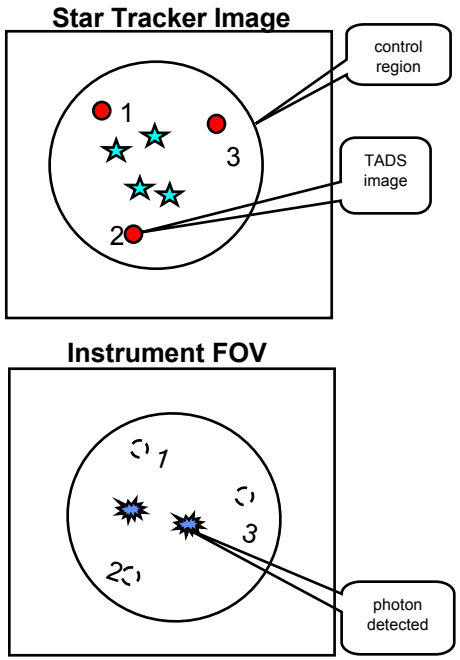
- Accuracy
  - 0.2 as (1σ), X and Y axes*
    - * *before in flight optical distortion calibrations*
  - 6.0 as (1σ), Z axis
- Detector / FOV
  - FOV is 5-by-5 degree
  - Clearance 3.54 degree ½ cone angle
  - 512 x 512 pixels
  - Pixel size: 15 x 15 micrometer = 35 x 35 as
- NEA
  - 0.11 arcsec about X and Y axes, 3.1 arcsec about Z axis
  - Bias error is 0.15 about X and Y axes, 4.0 arcsec about Z axis (1 sigma)
  - Centroiding to 1/100 of a pixel
- Senses 9.2 magnitude start (~50 stars)
  - Responds to 450-850 nm
- Guide Star Compensation for
  - Proper motion
  - Parallax
  - Velocity aberration and optical distortion
- Output quaternion at 2 Hz rate, Operable (at reduced accuracy) at up to 2.1 deg/s
- Acquisition time: 3 seconds
- Mass: 7.1 kg per unit; Power: 18 W per unit; Dimensions: 30.2 cm (L) x 13.3 cm (H) x 15.3 cm (W)
- 1553 bus
- Heritage: Spitzer

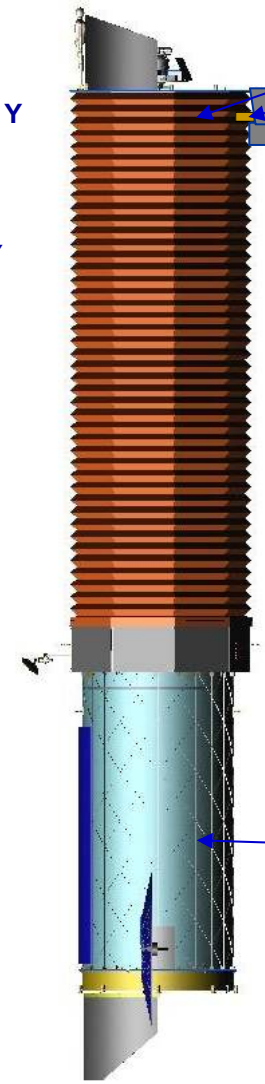
Source: **SIRTF Autonomous Star Tracker (SPIE Paper 4850-12), Roel van Bezooijen**

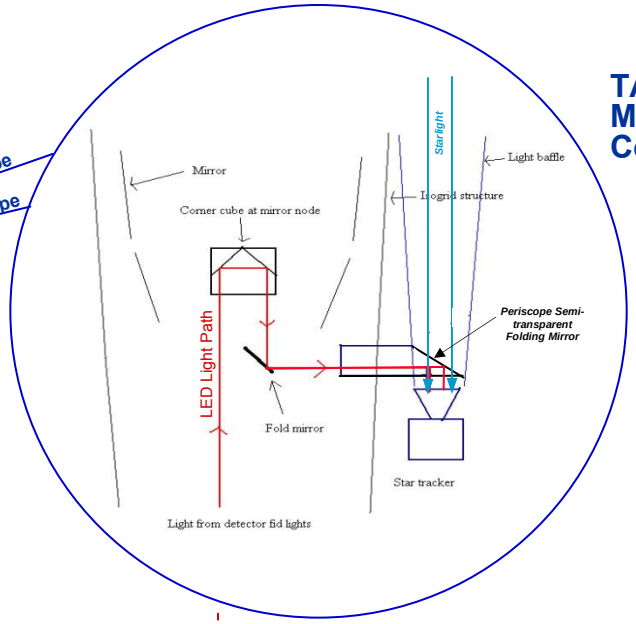
Telescope Aspect Determination System (TADS)

TADS Parameters

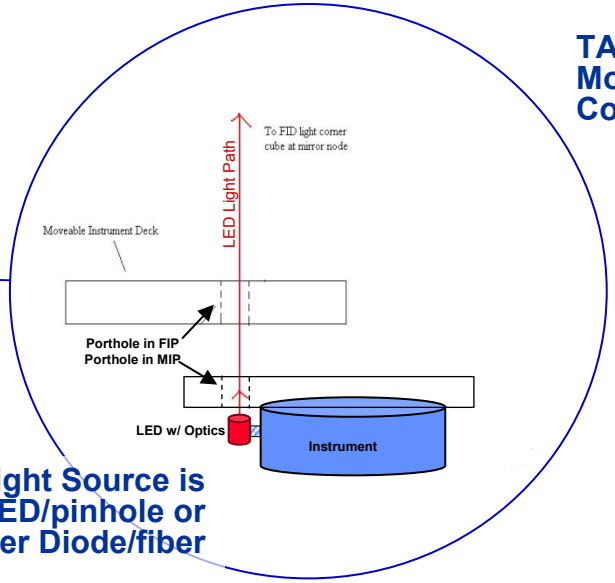
- **Accuracy Requirements:**
  - 0.8 arcsec (HPD) (.08 mm) in X and Y
  - 10 arcsec (HPD) (.08 mm) in in Torsion
- **Expected Performance:**
  - 0.11 arcsec.011 mm (3σ) in X and Y
- **Dynamic Range:**
  - +/- 100 arcsec (10 mm) in X and Y
  - +/- 20 arcmin (~10 mm) in Torsion







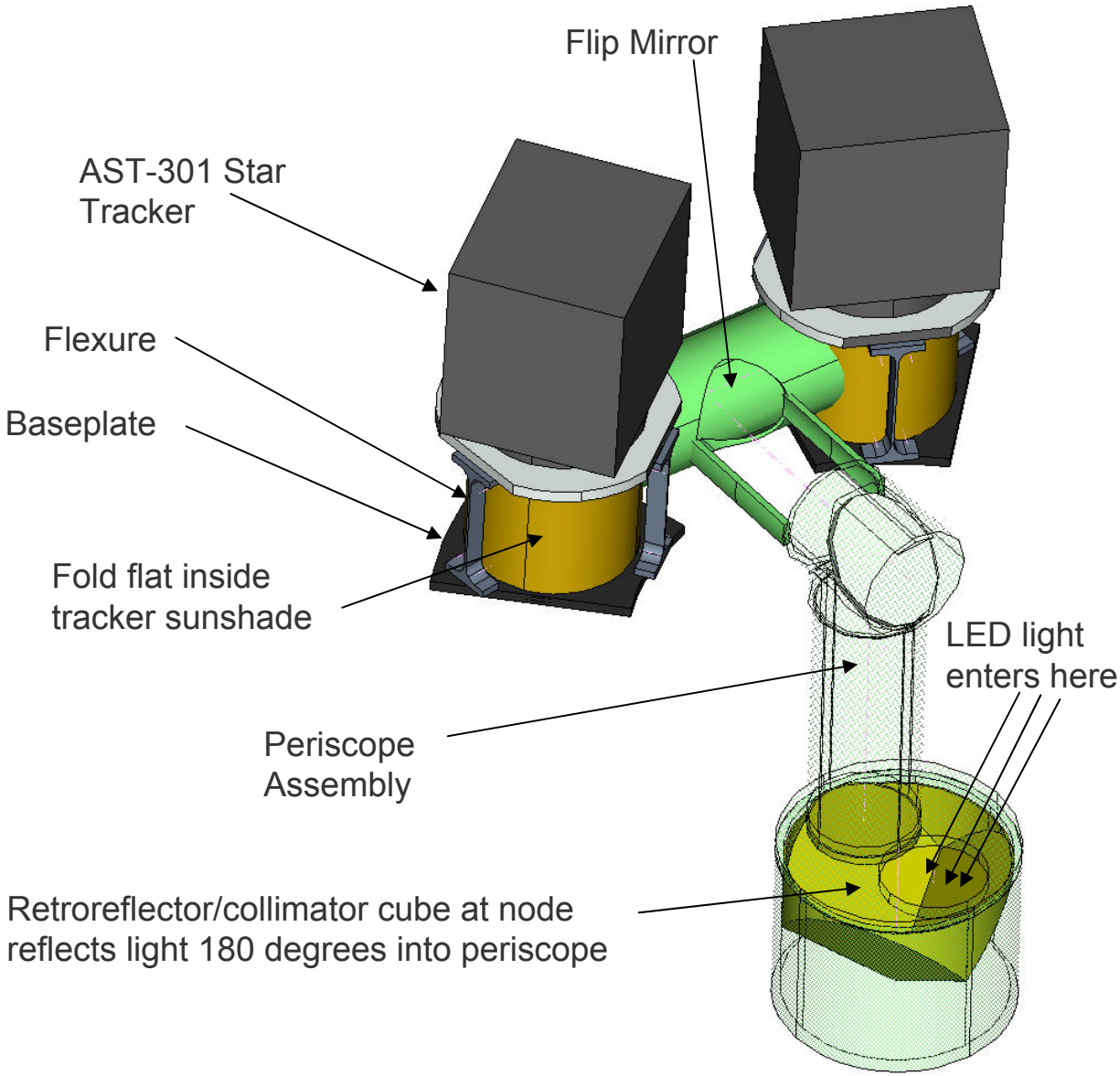
TADS Optics Module Components



TADS Instrument Module Components

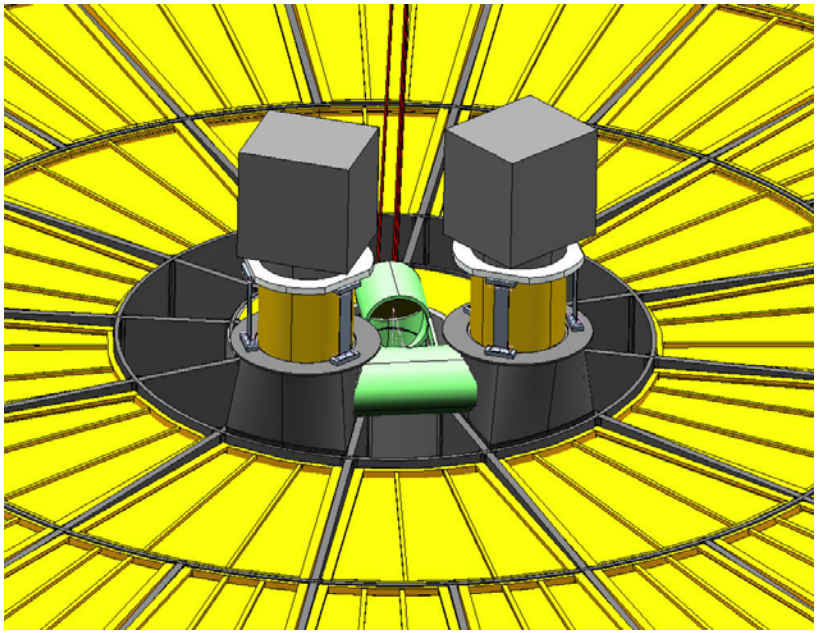
Light Source is LED/pinhole or Laser Diode/fiber

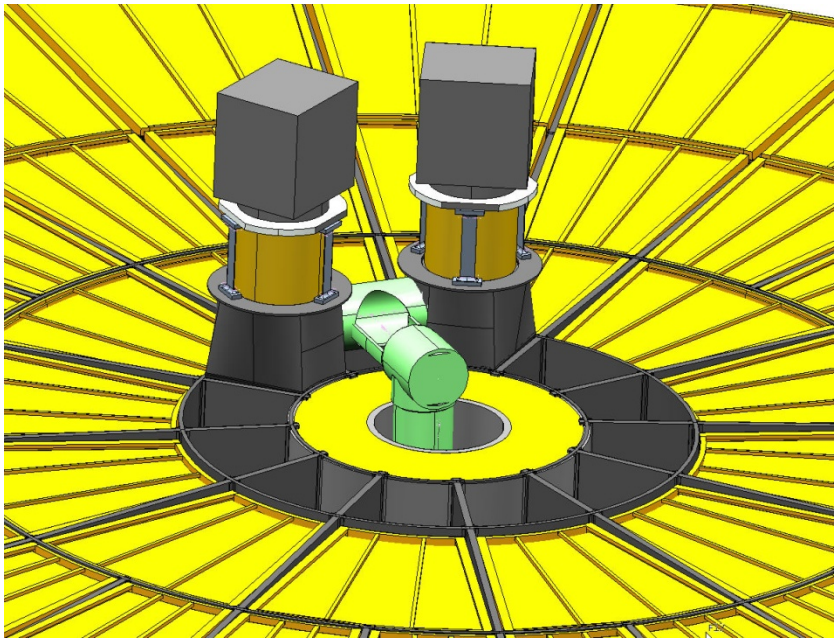
TADS Components



TADS

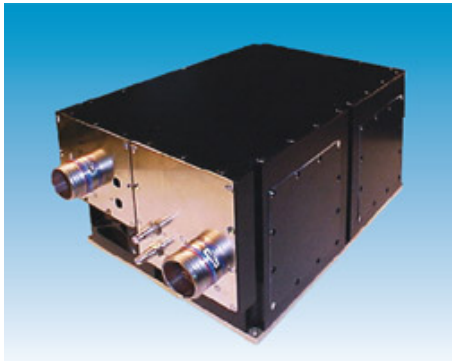
- A lightweight stand elevates the tracker lens assembly about 12 cm above the FMA.
- The periscope tube enters the stand where a fold mirror is located to turn the beam up and into the tracker FOV.
- Tracker mounts to 3 blade flexures via its Invar mounting flange.
- Flexures mount to top of the stand.





Adcole Coarse Sun Sensor and SIRU

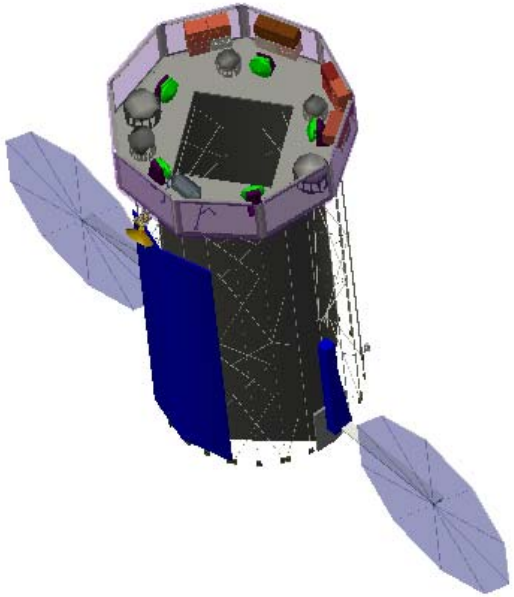
- Individual CSS detectors provide 2π steradian coverage
- 12 detectors distributed across the observatory provide redundant full 4π steradian coverage



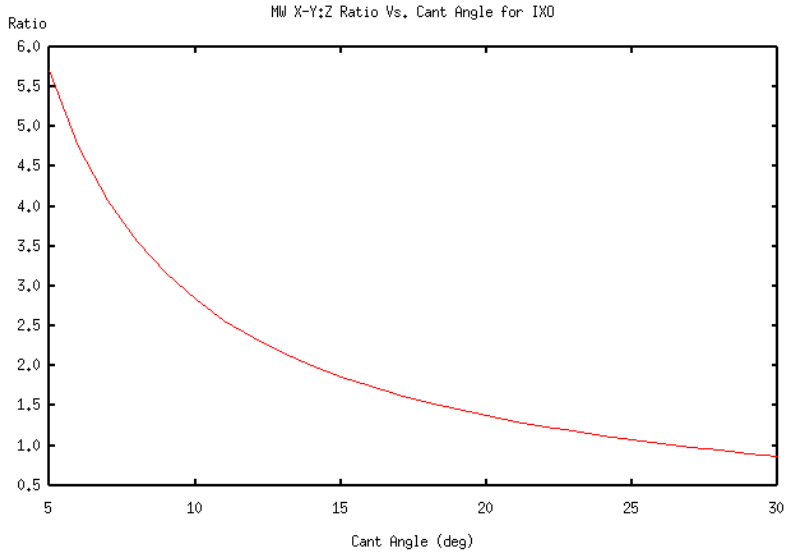
- Manufacture: NGES
- Technology: HRG 3 axis
- Gyro Performance
  - Angle Random Walk: 0.00015 deg/rt-hr
  - Angle White Noise: 0.003 arcsec/rt-Hz
- Range: 12 deg/sec
- Units Required: 1 (internally redundant)
- Data Interface: RS-422/1553
- Mass: 4.5 kg
- Power: 38 W
- Size: 18 x 15 x 29 cm
- Cost: $1500k

Reaction Wheel: Honeywell HR 16-150

- Momentum Storage
  - 150 NMS
- Reaction Torque
  - 0.2 Nm
- RS 422 I/F
- Mass: 15 kg per unit
  - HR(16) series rated at TRL-7
  - 150 Nms version not widely flown

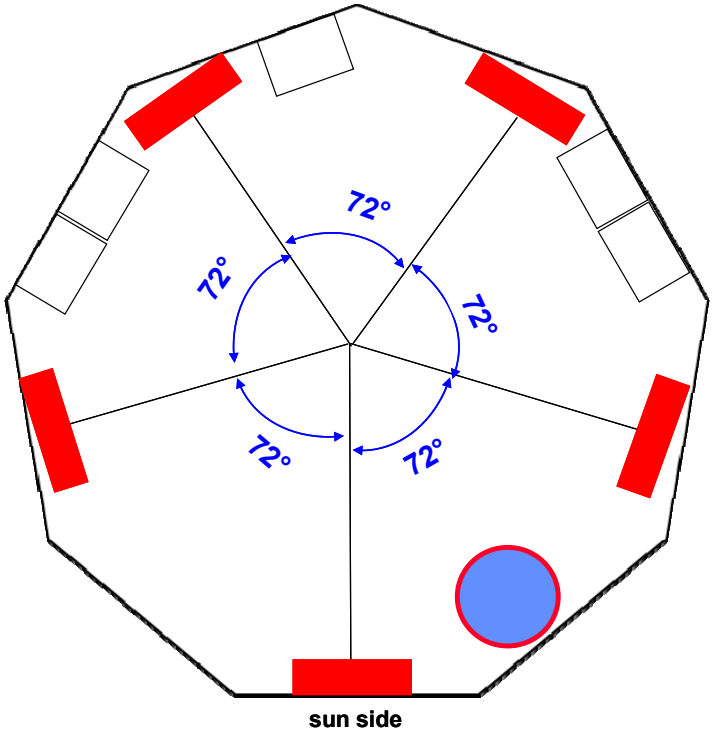


Proposed Reaction Wheel Orientation



Cant angle selected based on desired X-Y:Z ratio
A 4:1 ratio results in ~ 7 deg cant angle

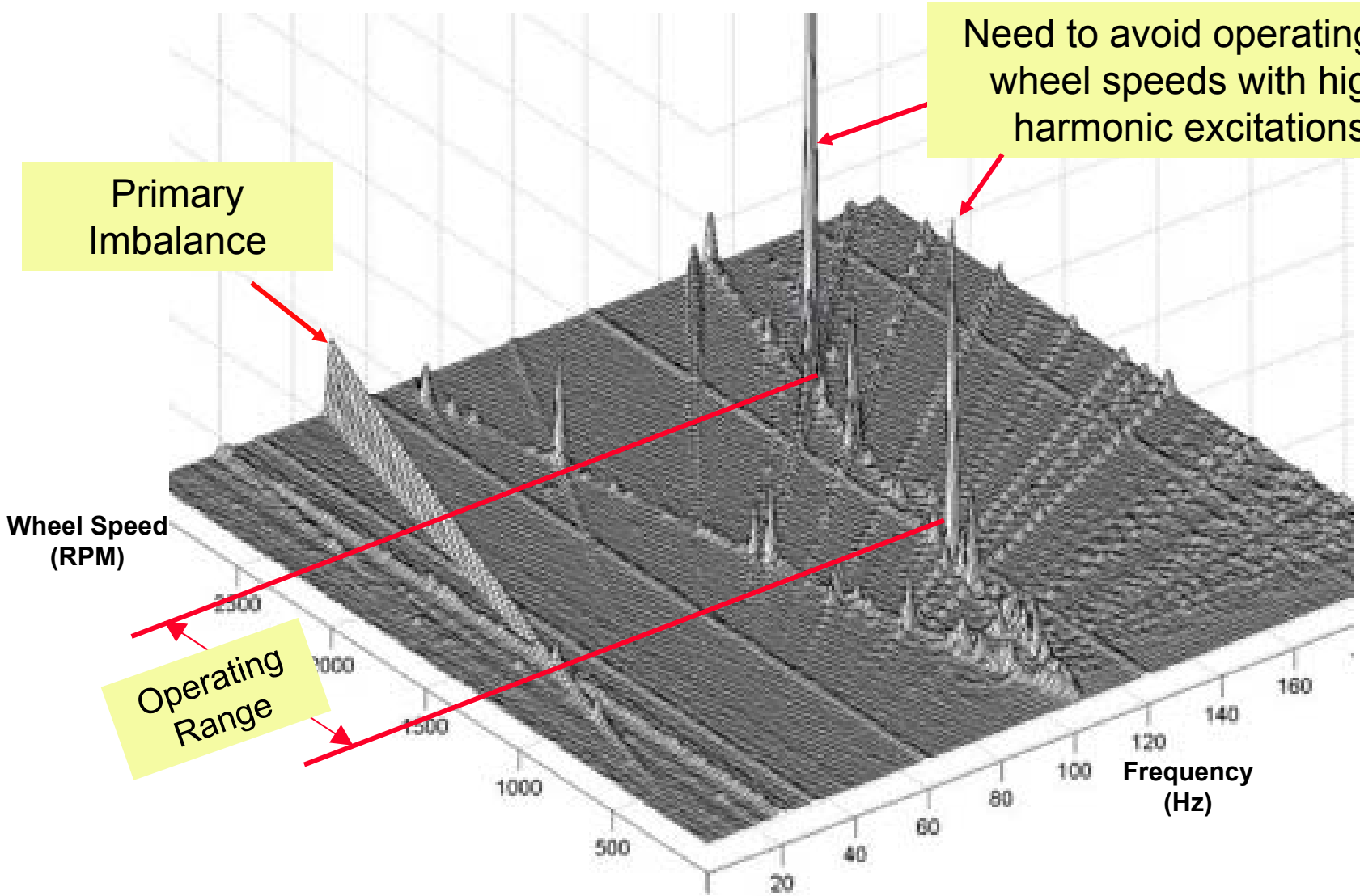
Reaction wheels canted slightly up out of page



Reaction Wheel Configuration Slew Capability

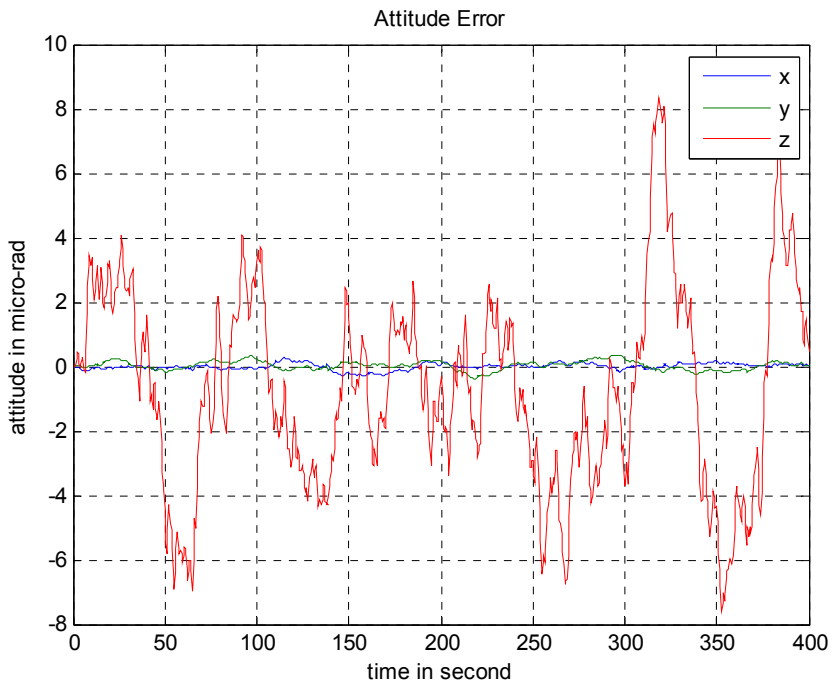
- Calculated for five Honeywell HR16 wheels
  - In pyramid configuration (like Spitzer)
  - Pyramid apex in Z direction
  - <10 deg cant angle (can be optimized depending on yaw (± 180 deg) versus roll (± 20) slew requirements)
- Each wheel
  - Angular momentum capability: 150 Nms
  - Torque capability: 0.2 Nm (is function of speed)
- Slew speed
  - 60 deg yaw: 0.52 hrs (margin not included)
  - 20 deg pitch: 0.41 hrs (margin not included)

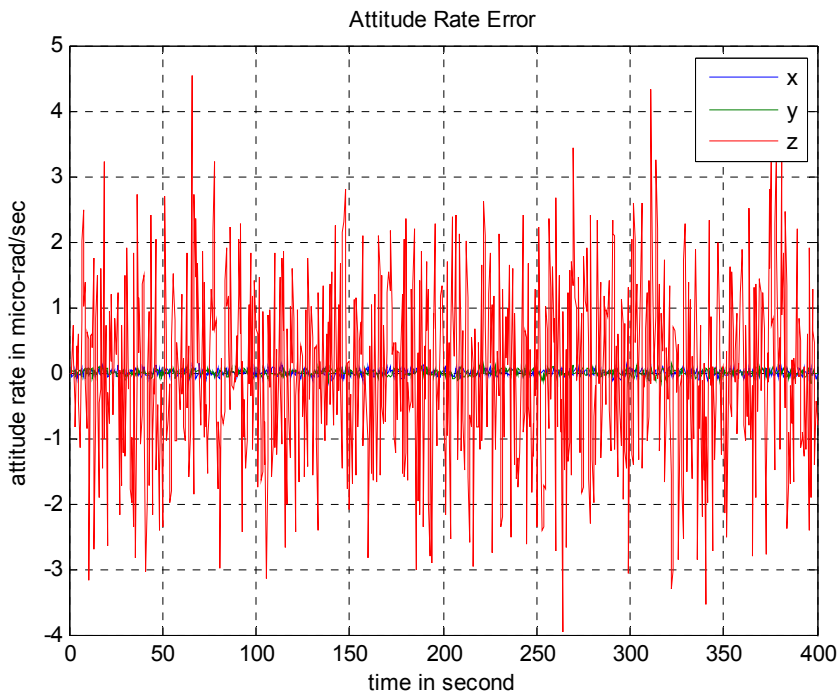
Reaction Wheel Disturbance Forces



Example Carpet Plot of In-plane Imbalance Forces From HR14 Dynamic Test

Pointing Performance





Spacecraft attitude errors due to LC

- **About X (1 sigma) = 0.025 arcsec***
- **About Y (1 sigma) = 0.025 arcsec**
- **About Z (1 sigma) = 0.64 arcsec**

**** Note: 1 arcsec = 4.85 micro-rad***

Spacecraft rate errors due to LC

- **About X (1 sigma) = 0.01 arcsec/s**
- **About Y (1 sigma) = 0.01 arcsec/s**
- **About Z (1 sigma) = 0.3 arcsec/s**

Analyses performed by Ich Pham (LMATC)

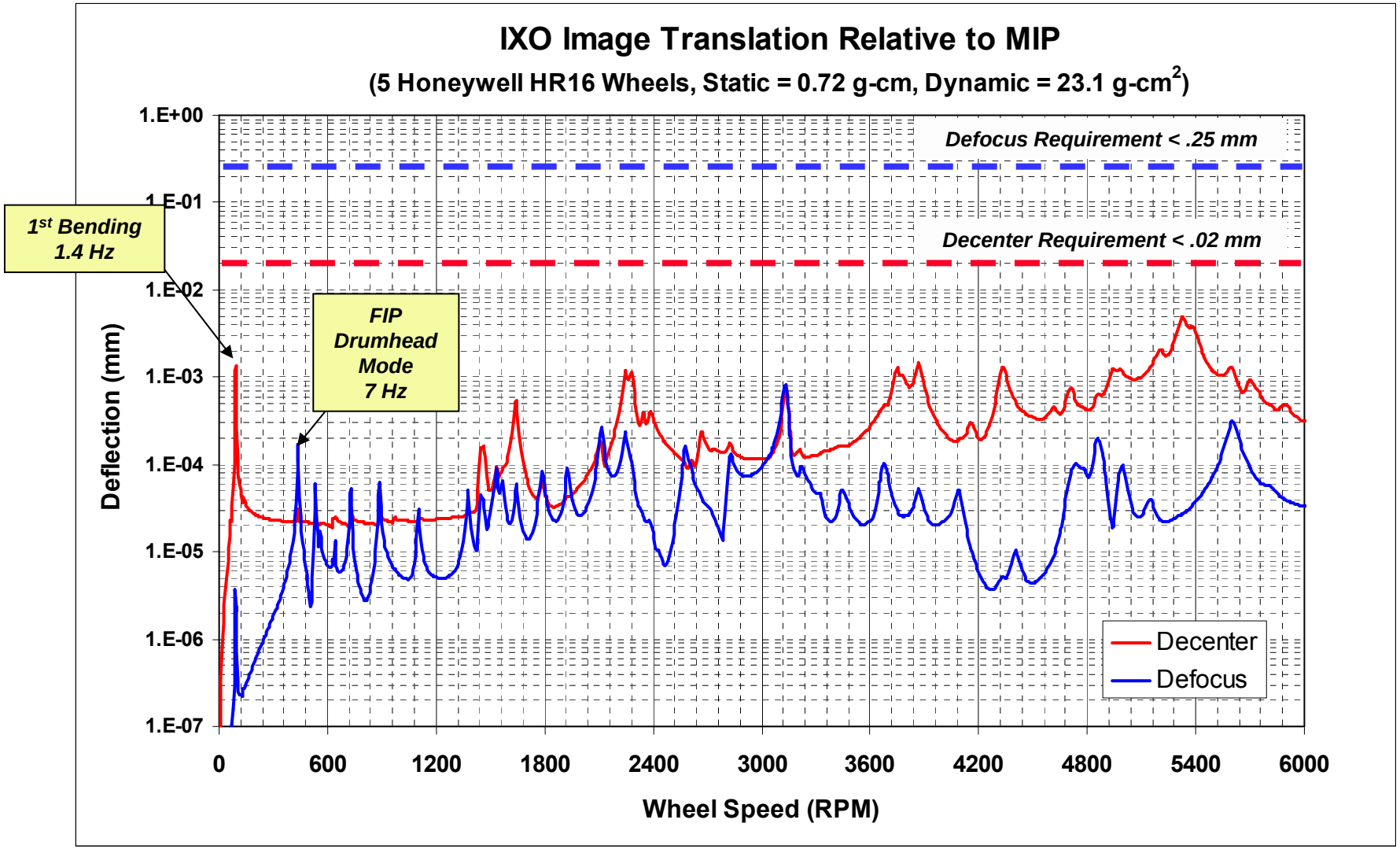
Slew Capability

- Calculated for four Honeywell HR16 wheels
  - In pyramid configuration (like Spitzer)
  - Pyramid apex in X direction
  - 30 deg cant angle (can be optimized depending on yaw (± 180 deg) versus pitch (± 20) slew requirements)
- Each wheel
  - Angular momentum capability: 150 Nms
  - Torque capability: 0.2 Nm (is function of speed)
- Slew speed
  - 60 deg yaw: 0.52 hrs (margin not included)
  - 20 deg pitch: 0.41 hrs (margin not included)

Jitter Analysis Parameters

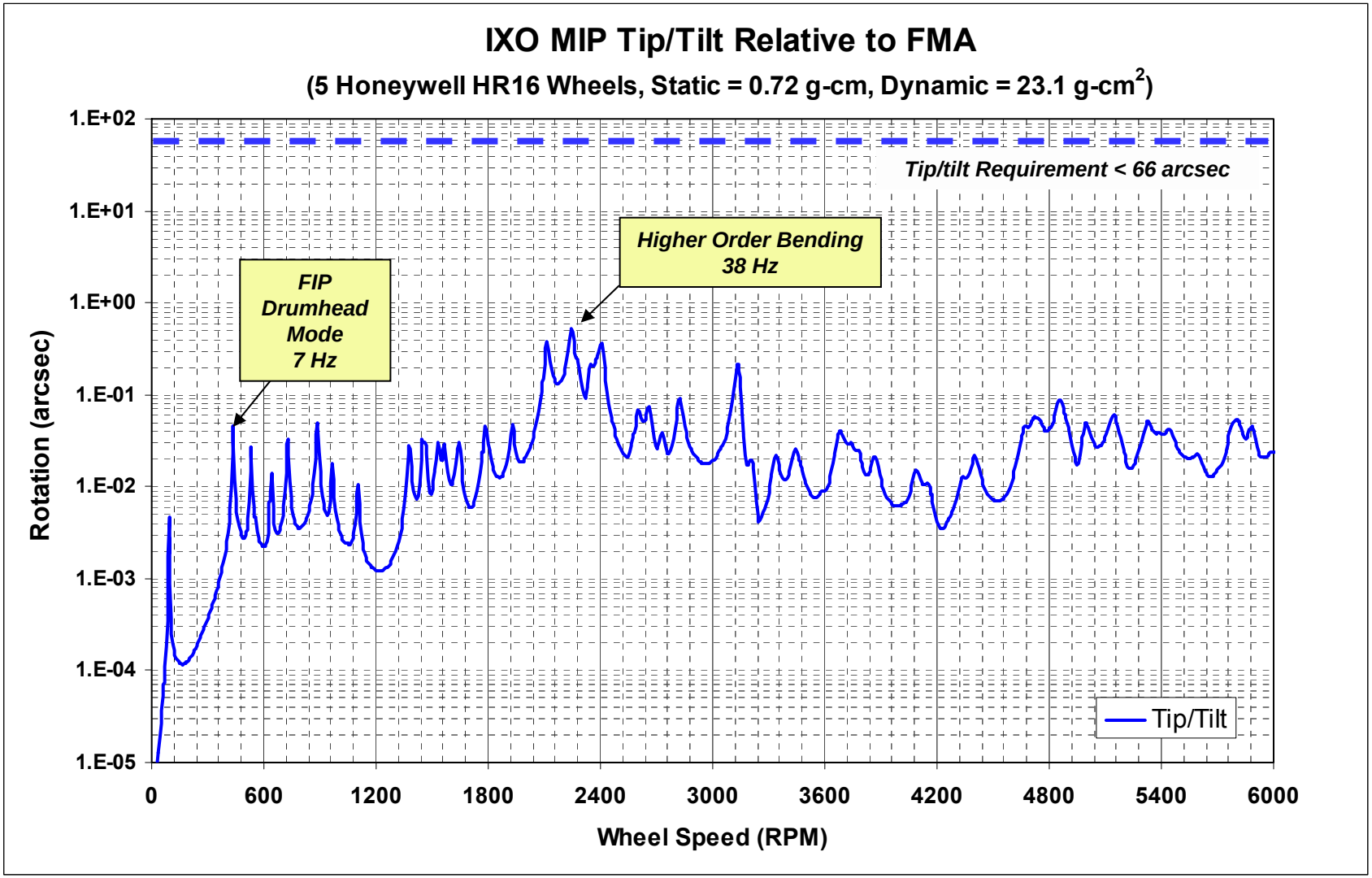
- 150 N-m-s HR16 Wheel Imbalances (derived from datasheet)
  - Static = .72 g-cm, Dynamic = 23.1 g-cm^2
  - Only primary imbalance considered
  - Refined analysis will include affects of higher harmonics
- Use 0.5% modal damping
- Apply disturbances to all 5 wheels
  - RSS all wheels (conservative: assumes all wheels operate at same speed)
  - Calculate optical element jitter and LOS pointing error versus wheel speed

Jitter Analysis Results



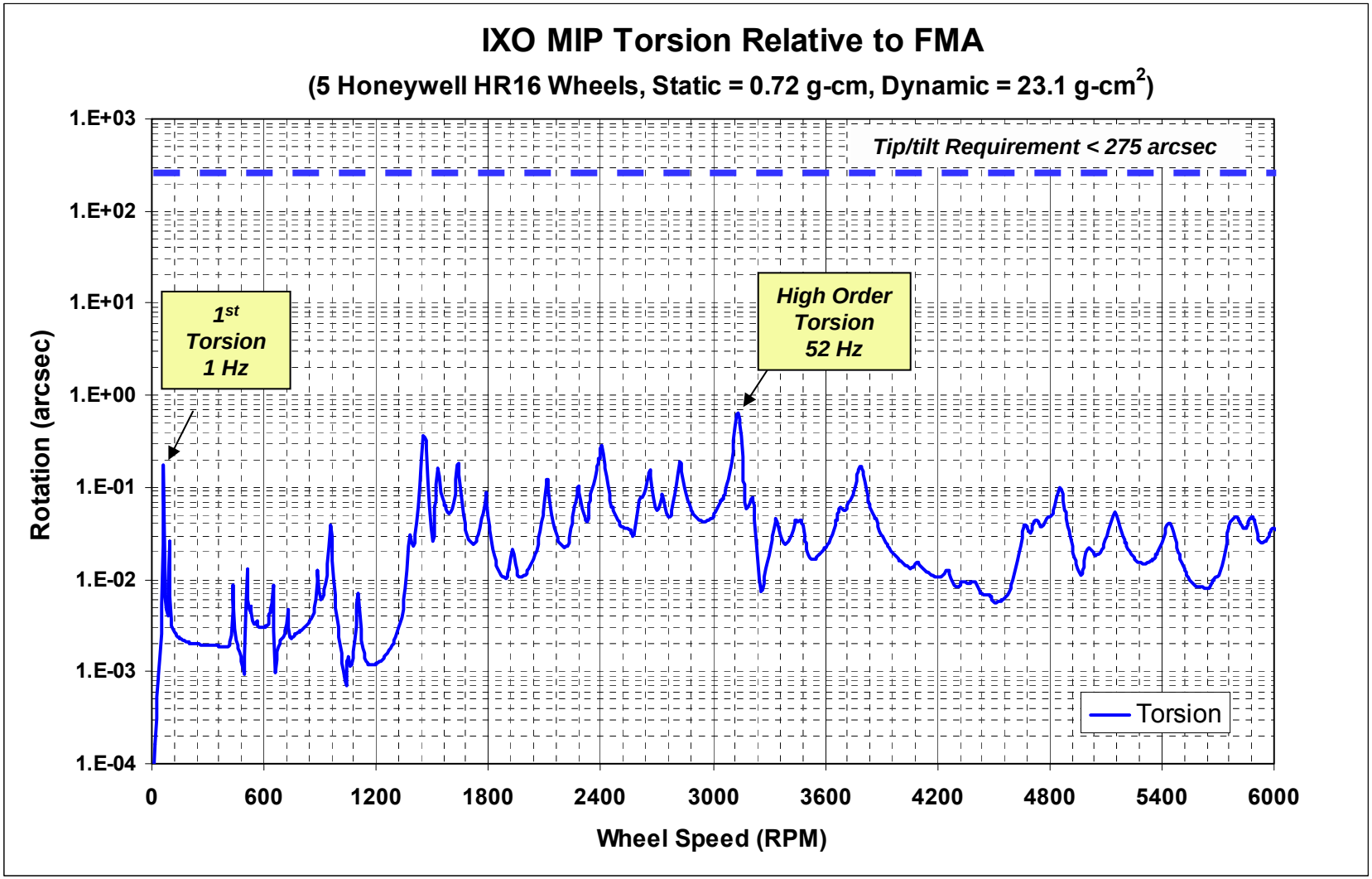
Responses < Requirements

Jitter Analysis Results (Tip / Tilt)



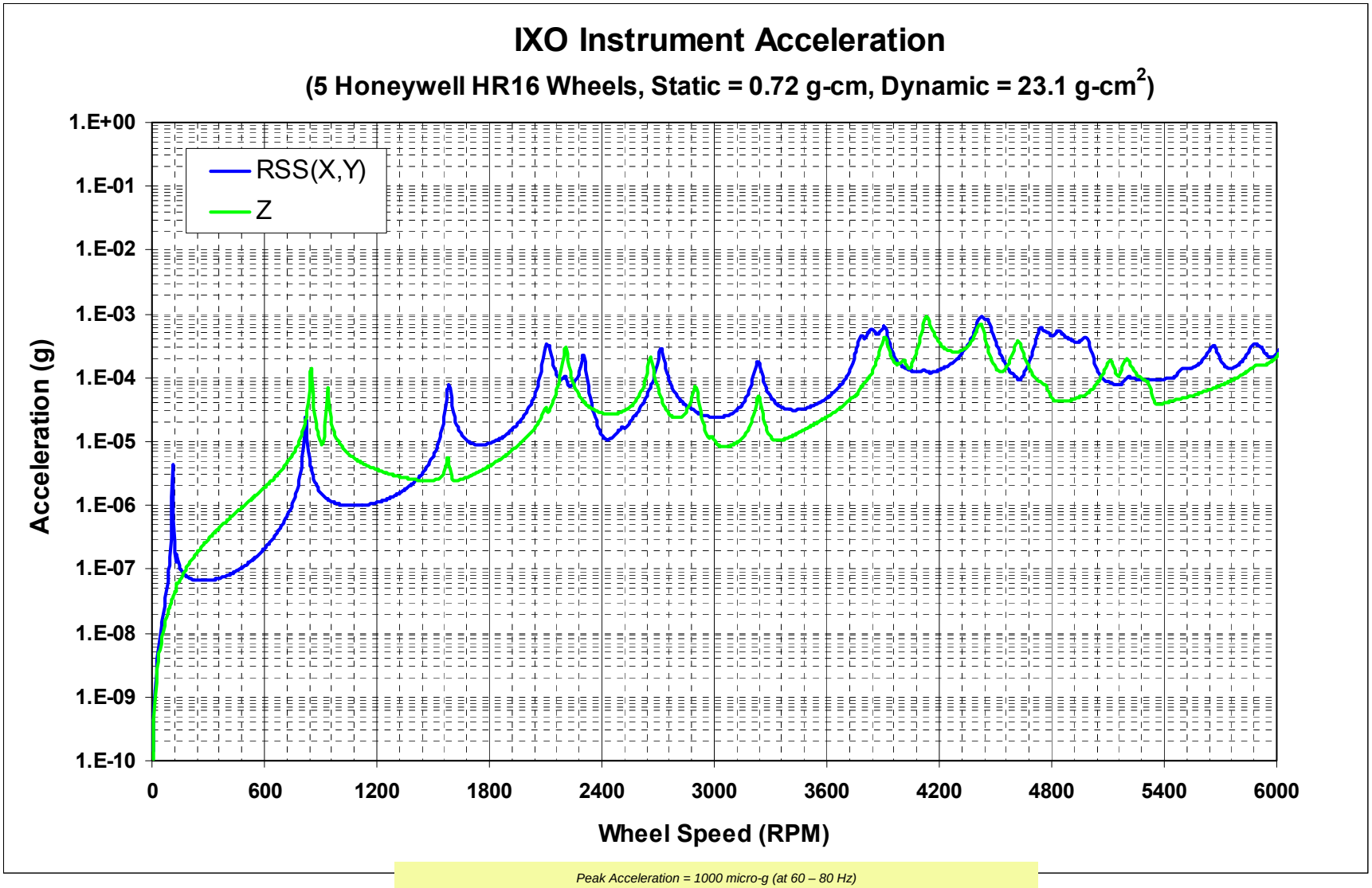
Responses << Requirement

Jitter Analysis Results (Torsion)



Responses << Requirement

Instrument Accelerations



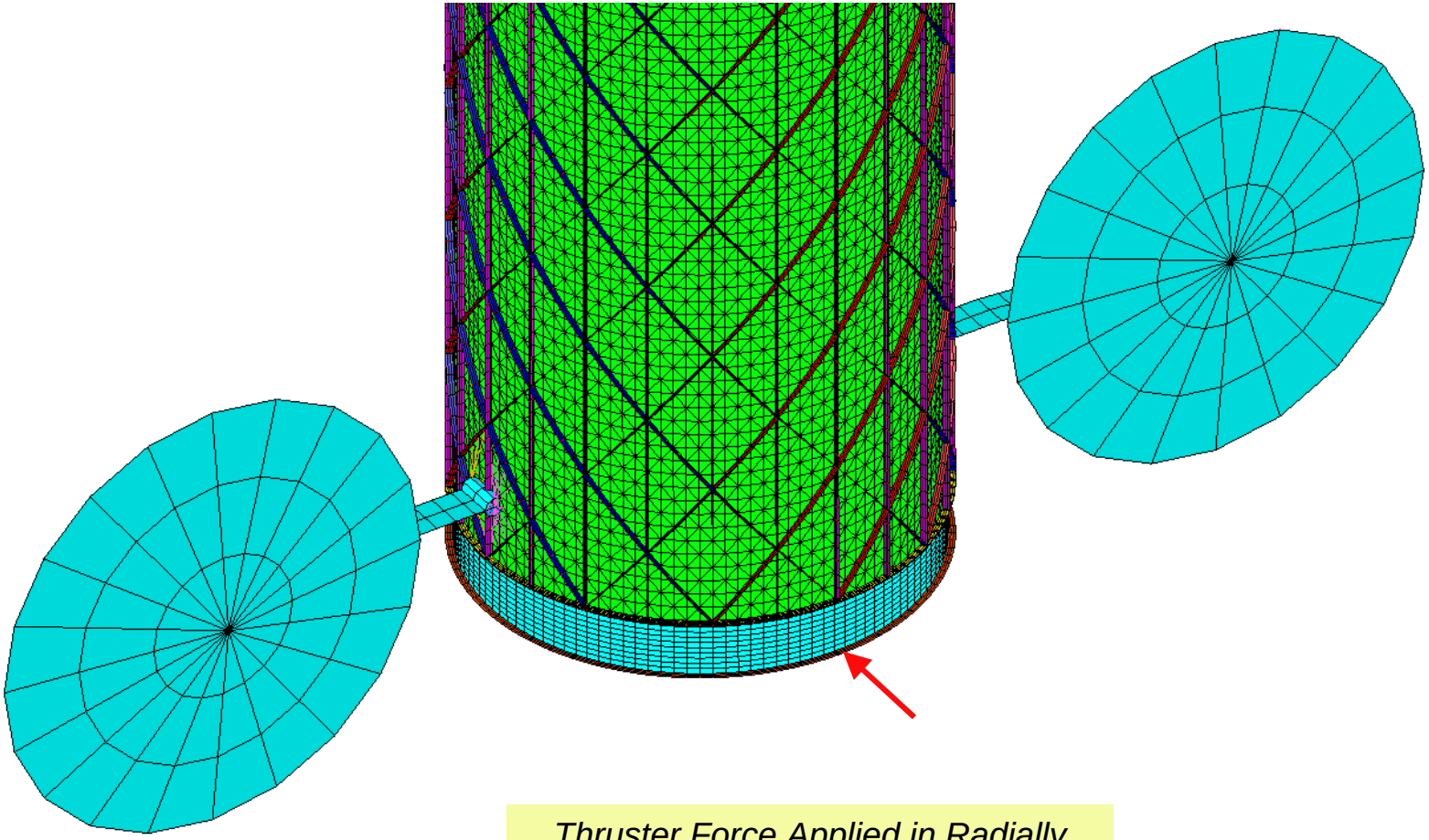
Peak Acceleration = 1000 micro-g (at 60 – 80 Hz)

Impact of Solar Pressure Offload (0.9 N Thruster) Firing

- Use highly reliable MR103H Aerojet thruster used for Voyager and Cassini
- Attitude Deviation versus Pulse Length
  - 0.11 s burn every 18 minutes: 0.165 arcsec deviation
- Number of 0.11 s Thruster Firings:
  - 300,000 over 10 Years (once per 18 min)
    - Voyager had 500,000 burns from single thruster, using same thruster
  - Total amount of propellant: 15 kg
- Assumes IXO config with two 3.35 m dia Circular Ultraflex Solar Arrays

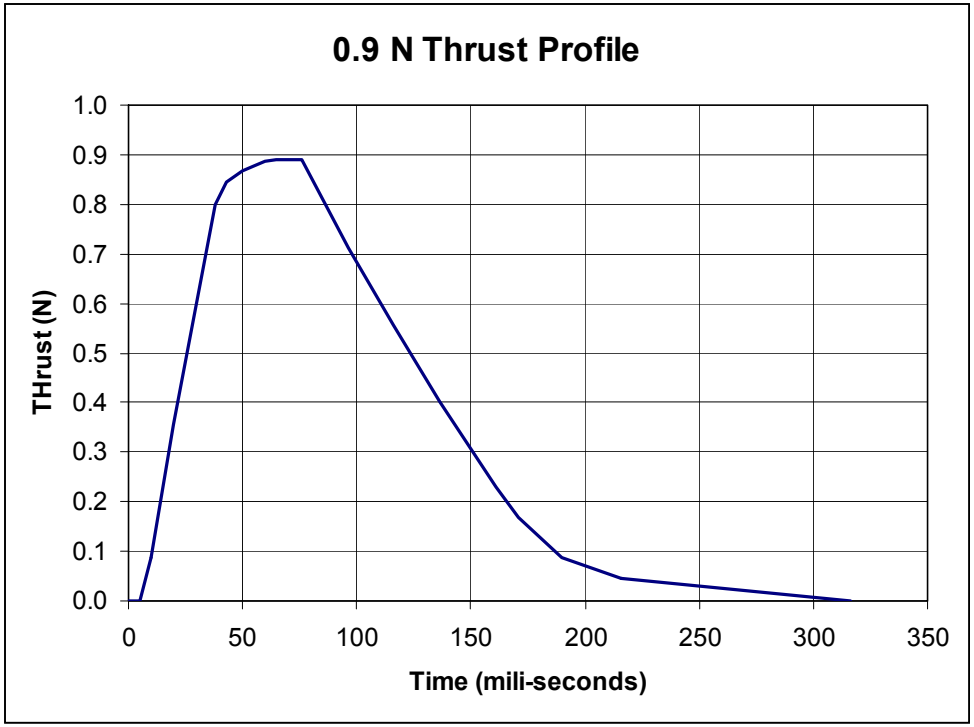
0.9N Thruster Force

- **Use highly reliable MR103H Aerojet thruster used for Voyager and Cassini**



Thruster Force Applied in Radially Inward Direction to +X Side of Spacecraft Adapter Flange

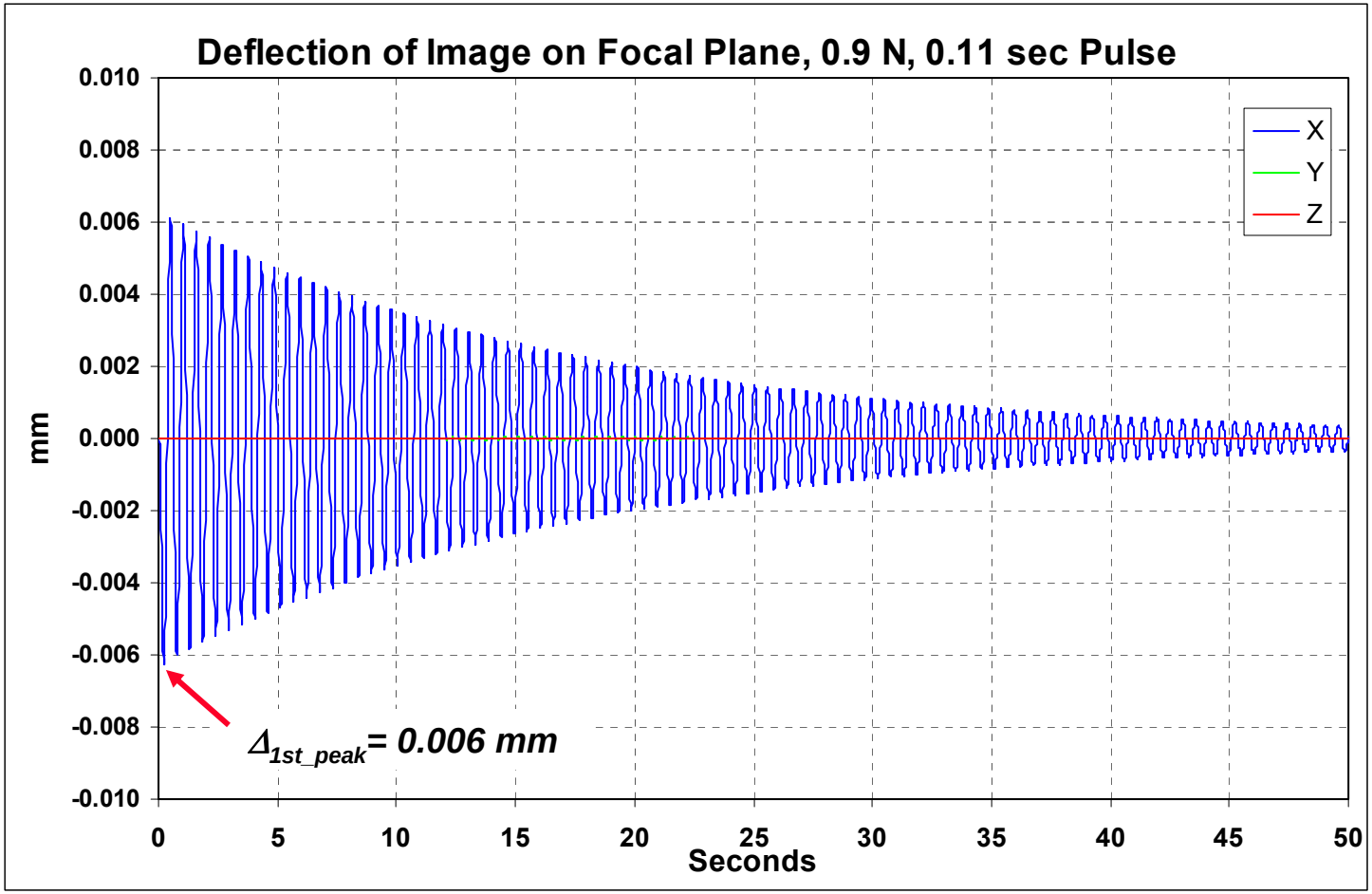
0.9N Thruster Pulse and Model Parameters



Total Impulse = 0.1 N-s
Derived from Astrolink jitter analysis profile

- **Modal damping = .5% of critical damping**
- **232 modes included in solution space (0 to 150 Hz range)**
- **2500 time steps at .001 second per step**

0.9N Thruster Firing Induced Vibration Decay

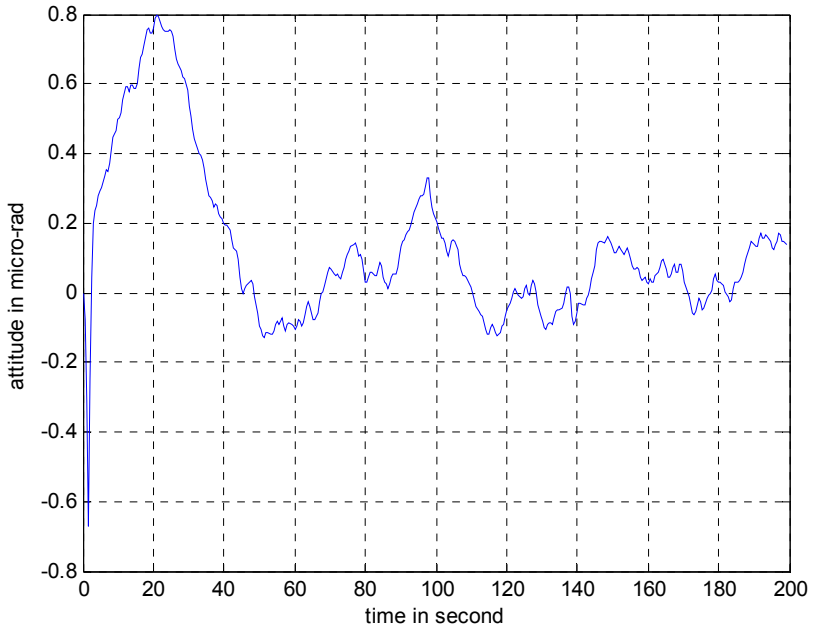


$$\frac{\Delta_{nth_peak}}{\Delta_{1st_peak}} = e^{-2\pi n\xi/(1-\xi^2)^{1/2}} \Rightarrow \Delta_{peak_at_time_t} = 0.006e^{-.0575t}$$

Deflection Decays to less than .001 mm after 30 seconds

0.9N Thruster Firing Induced Temporary Attitude Deviation - Integrated FEM + Control System Result

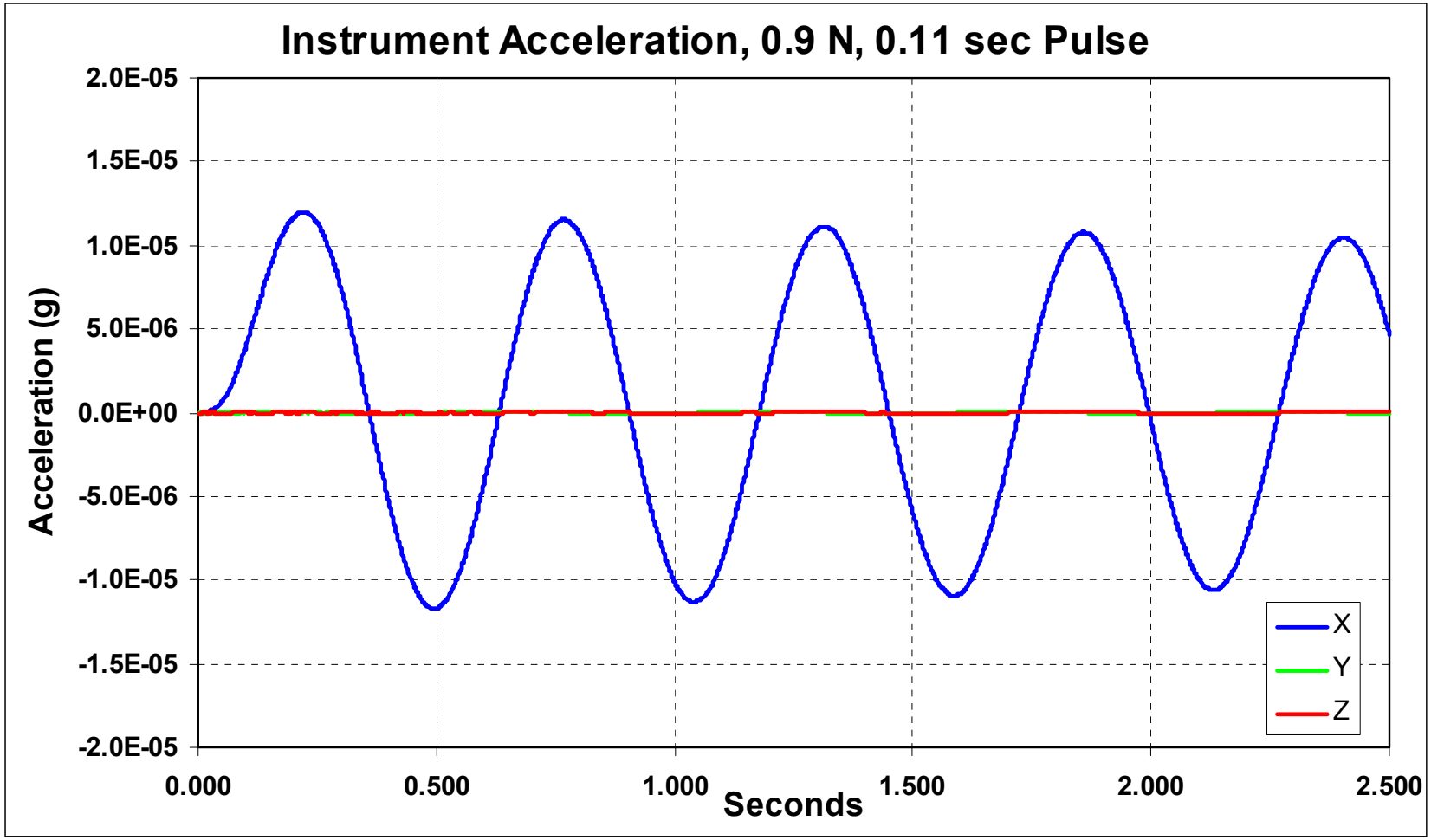
- 0.9 N Thruster on for 0.11 s; generates 0.1 Ns impulse and 0.62 Nms angular momentum delta
- RWL feed forward of -0.2 Nm for 3.1 seconds
- Thruster firing centered relative to 3.1 second RWL feed forward period



- Resulting attitude excursion about Y axis: 0.165 arcsec

Integrated FEM + Control System Result

Accelerations due to 0.9 N Thruster Firing



Peak Acceleration = 12 micro-g

Thermal

Orbit Thermal Environment

- L2 provides excellent thermal environment for passive (radiative) cooling
  - Zero % eclipses during entire mission
  - Earthshine and moonshine negligible
  - Thermal disturbances
    - Sun angle changes due to ±20º roll and ±20º pitch
    - Variation of solar constant
- Charged particles environment may require electrically conductive thermal coatings

Spacecraft Bus - Temperature Requirements

- Electronics Components
  - -10°C to +40°C operational and -20°C to +50°C survival
- Solar Array Temperatures
  - Operational -100°C to +100°C (TBR)
- Li Ion Battery Temperatures
  - Operational 0°C to +30°C
- Propulsion System for all modes
  - All components maintained at 10°C to 40°C (hydrazine freezes at 2°C), except NTO Tank that is -10°C to 40°C

S/C Bus Component Thermal Control Requirements

Subsystem	Component	Dimensions (cm) HxDxW (2)	Unit mass (kg)	Power (W) Science	Downlink	Slew	Safehold	Peak	Temperature limits (°C) Operating	Survival
RF Comm	DSN S/Ka-Band transmitter	25x25x20	6.2	24	30	24	24	30	-20/50	-30/70
	10 Watt TWTA	30x30x27	12.0	20	30	20	20	30	-20/50	-30/70
	S-band 5 watt power amplifier	13x13x13	1.0	0	20	0	0	20	-20/50	-30/70
C&DH	Electronics Unit	50x50x40	48.0	125	133	135	119	153	-20/50	-30/70
Propulsion	Hz Tank PSI 80364-1	58 Dia	11.3						10/40	
	NTO Tank PSI 80353-1	48 Dia	7.7						-10/40	
	COPV He Tank PSI 80412-1	70x33 Dia	7.0							
	AMPAC 22N Biprop Thrusters					5			10/40	
	Pressure Transducers			5	5	5	5	5	10/40	
EPS	Power System Electronics	50x50x40	50.0	161	162	155	129	226	-20/50	-30/70
	50 AH Li-Ion Battery (1)	30x30x30	14.0	5.6	5.6			5.6	15/35	
ACS	Gyros	12x12x12	0.8	12	12	12	12	12	-20/50	-30/70
	Reaction Wheels (each of 5)	13x42 Dia	14.0	6.4	6.4	63	6.4	84	-20/50	-30/70
	Star Tracker Processing Unit	12x12x12	0.8	3.6	3.6	3.6		3.6	-20/50	-30/70
Harness				6.4	6.5	6.2	5.2	9		

XMS Thermal Interface Requirements

Instrument Thermal Interface Requirements					
Payload	**Element**	**Operating**	**Annealing**	**Survival - (Off)**	**Comments / Source**
XMS	Dewar Assembly	-33C to 27C		-100C to 50C	**CDF = 20C**
	Filter Wheel	-20C to 50C		-20C to 50C	
	Pre-Amplifier/BiasBox (PBB)	-20C to 50C		-30C to 70C	
	Feedback/Controller Box (FCB) -1	-20C to 50C		-30C to 70C	
	Feedback/Controller Box (FCB) -2	-20C to 50C		-30C to 70C	
	Feedback/Controller Box (FCB) -3	-20C to 50C		-30C to 70C	
	Feedback/Controller Box (FCB) -4	-20C to 50C		-30C to 70C	
	Pulse Processing Electronics (PPE)	-20C to 50C		-30C to 70C	
	ADR Controller (ADRC)	7C to 27C		-30C to 70C	
	Cryocooler Compressor	10C to 40C		-20C to 50C	
	Cryocooler Control Electronics (CCE)	10C to 40C		-30C to 70C	
	Filter Wheel Control Electronics (FWC)	10C to 40C		-30C to 70C	
	Power Distribution Unit (PDU) -1	10C to 40C		-30C to 70C	
	Power Distribution Unit (PDU) -2	10C to 40C		-30C to 70C	

WFI / HXI Thermal Interface Requirements

Instrument Thermal Interface Requirements					
Payload	**Element**	**Operating**	**Annealing**	**Survival - (Off)**	**Comments / Source**
(WF&HX)I	Focal Plane Assembly [(WF&HX)I-FPA]				
	Focal Plane Assembly - cold part	-63 +/- 0.1 C		-103 to 77 C	Thermal isolation required between camera and deck. Cooling is assumed to be through cold finger to radiator + local heater regulator. Provide 10C colder interface for detector (i.e. -73 C)
	Focal Plane Assembly - warm part	0 to 40 C		-40 to +85 C	Flex Brackets (2)
	HXI Sensor Head (HXI-S)	-20 +/- 2 C	5 ±2 C	-40 to +40 C	Internal to WFI-FPA - Set by Instrument
	WFI Hemisphere Pre-Processor-1	0 to 40 C		-40 to +85 C	
	WFI Hemisphere Pre-Processor-2	0 to 40 C		-40 to +85 C	
	HXI Analog Electronic Unit (HXI EA)	0C to 40 C	0C to 40 C	-40 to +40 C	
	WFI Brain Frame Builder-1&2	0 to 40 C		-40 to +85 C	
	WFI Power Conditioner-1 (control)	0 to 40 C		-40 to +85 C	
	WFI Power Conditioner-2 (control)	0 to 40 C		-40 to +85 C	
	HXI Digital Electronics (HXI DE)	0C to 40 C	0C to 40 C	-40 to +40 C	
	HXI PSU (HXI PSU)	0C to 40 C	0C to 40 C	-40 to +40 C	

XGS Thermal Interface Requirements

Instrument Thermal Interface Requirements					
Payload	**Element**	**Operating**	**Annealing**	**Survival - (Off)**	**Comments / Source**
XGS	Grating Arrays	20 +/- 1 C		18 to 53C	/ Jay email 7-18-08 for operating
	CCD Camera	-90 +/- 10C		-120 to 70C	5 W dissipation / Tom from survival
	CCD Detector	-90 +/- 10C		-120 to 70C	
	Detector Electronics Assembly (DEA)	-30 to 10C		-30 to 55C	
	Digital Processing Electronics (DPE)	-30 to 10C		-30 to 55C	
	Power Supply & Mechanism Controller	-30 to 10C		-30 to 55C	

XPOL Thermal Interface Requirements

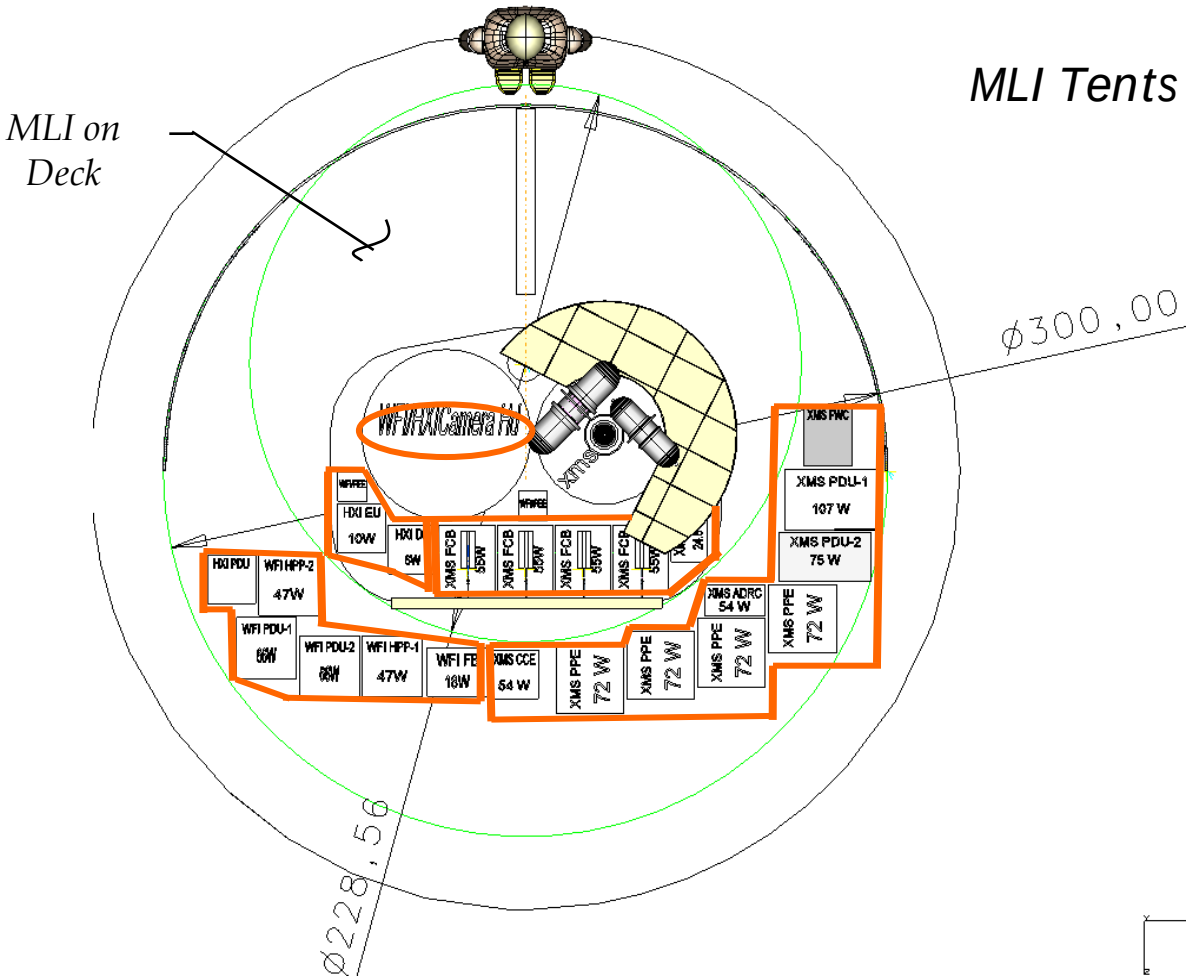
Instrument Thermal Interface Requirements					
Payload	**Element**	**Operating**	**Annealing**	**Survival - (Off)**	**Comments / Source**
XPOL	Focal Plane Assembly (XPOL-FPA)				
	Detector + FEE	+5 ±1 C		-15 to +45 C	Internal local heater regulator
	Filter Wheel	0C to 40C		-15 to +60 C	
	Backend Electronics (XPOL-BBE)	0C to 40C		-15 to +60 C	
	Control Electronics (XPOL-CE)	0C to 40C		-15 to +60 C	

HTRS Thermal Interface Requirements

Instrument Thermal Interface Requirements					
		Operating	Annealing	Survival - (Off)	Comments / Source
HTRS	Focal Plane Assembly (HTRS-DEU)				
	Detector	-20 +/- 2 C		-40 to +35 C	
	FEE + Filter Wheel	0C to 40C		-40 to +35 C	
	Central Electronic Unit (HTRS-CEU)	0C to 40C		-40 to +35 C	

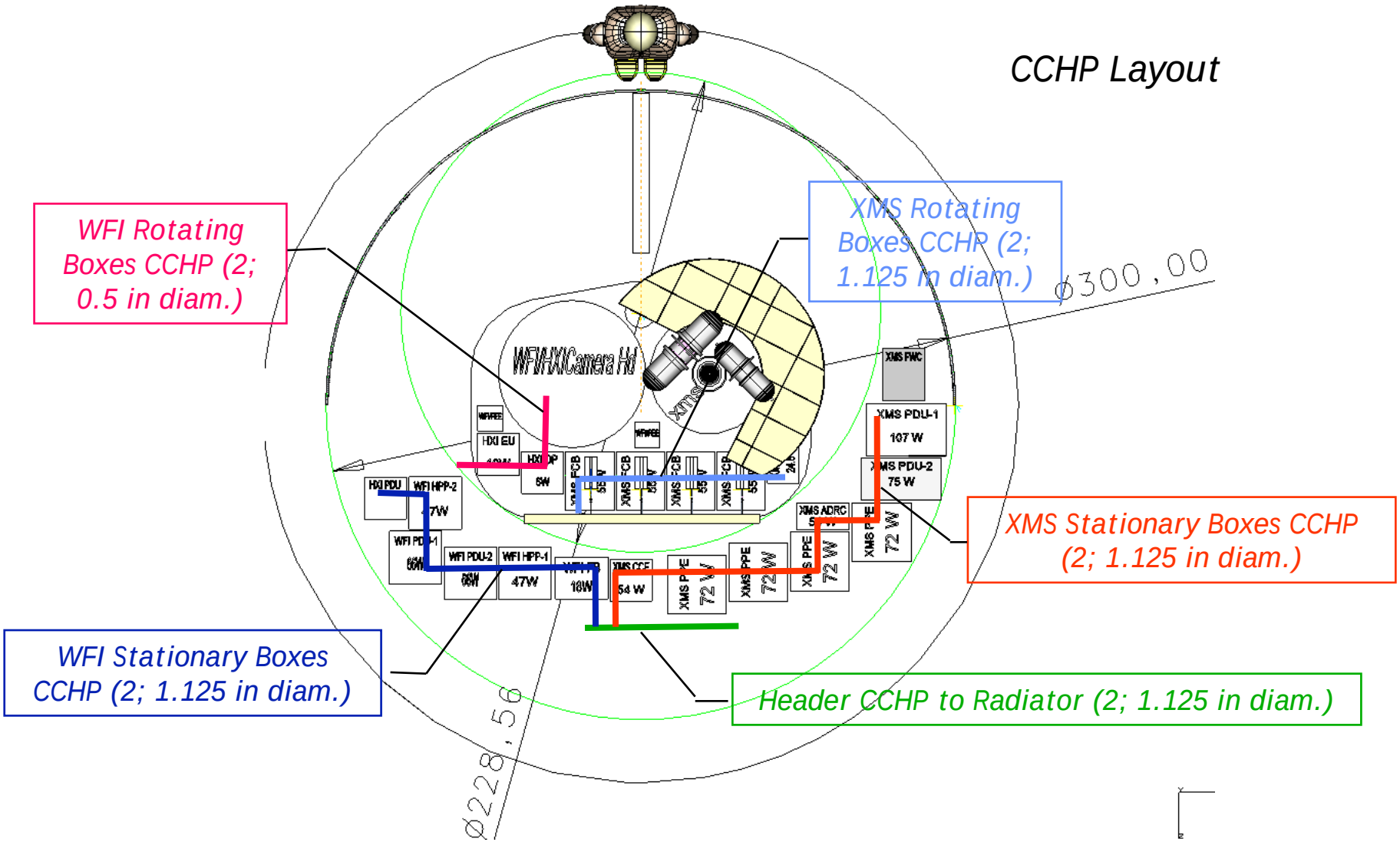
Instrument Module Thermal Configuration - MLI

- *MLI on exterior of electronics boxes and Cryostat to minimize survival heater power and thermal effect of sunshield*
- *MLI on exposed areas of radiator backside and platform*



Instrument Module Thermal Configuration– Radiators

Shared Radiator for Stationery Boxes



Thermal Design - IM Radiator Mass

- *Estimate based on Mode 2 + full XMS average power.*
- *VCHP will accommodate lower power modes*
- *Estimate includes facesheets, core, adhesives, coatings, MLI on back, plus 25% for structure*
- *Temperatures and heat loads from observatory thermal model*

	Area (m^2)	Mass (kg)
MIP electronics	0.88	5.1
WFI cold finger	0.38	2.6
XMS compressor	0.71	4.2
FIP electronics	1.25	7.4
XGS camera	0.30	1.9
Total		21.2

Thermal Design - Heat Pipe Mass Estimate

		Ea	No req'd	Ext
Adapter	CCHP	5.6	3	16.7
SCB	CCHP	8.3	2	16.5
FIP	VCHP	3.4	2	6.9
MIP	VCHP	3.1	2	6.3
Subtotal		20.4		46.4
Contingency				30%
Total				60.3

Notes: Number required includes redundancy
SCB heat pipe weight includes mounting pads
Heat pipes are flight proven NH3/Al extrusion design, 350 W-m capacity

Thermal Design - MLI Mass Estimate

	Area (m2)	Mass (kg)
Adapter	8.3	2.6
FMS	67.9	21.5
SCB	5.4	1.7
FIP panel	18.2	5.7
FIP elex radiator	0.7	0.2
MIP panel	3.8	1.2
MIP elex radiator	1.8	0.6
WFI cold radiator	0.5	0.1
Subtotal		33.7
Contingency		30%
Total		43.8

Notes: 20 layer blanket, .25 mil embossed Mylar inner layers
2 mil Kapton outer layers
Does not include deployable shroud

Thermal Design - IM Radiator Mass

- *Estimate based on Mode 2 + full XMS average power.*
- *VCHP will accommodate lower power modes*
- *Estimate includes facesheets, core, adhesives, coatings, MLI on back, plus 25% for structure*
- *Temperatures and heat loads from observatory thermal model*

	Area (m^2)	Mass (kg)
MIP electronics	0.88	5.1
WFI cold finger	0.38	2.6
XMS compressor	0.71	4.2
FIP electronics	1.25	7.4
XGS camera	0.30	1.9
Total		21.2

FMA Thermal Control – Independent Power System

- Observatory to maintain Survival Mode indefinitely (even after LV Separation w/ no S/As deployed)
- The 8 m2 body mounted solar array, combined with a robust "no-microprocessors" Sun-positive Safe-Mode allows maintaining FMA Temperatures
- FMA Temperature Controller has independent unregulated power system: S/A output directly to Hetares
  - About half of the strings on the body mounted array are unregulated, routed directly to the FMA Temperature Controller
- FMA Temperature Controller regulates directly to Temperature regardless of voltage, or current
  - via single FET
  - Every Watt dissipated in the FETs is used: FETs are also mounted on the Pre-Collimator Blades

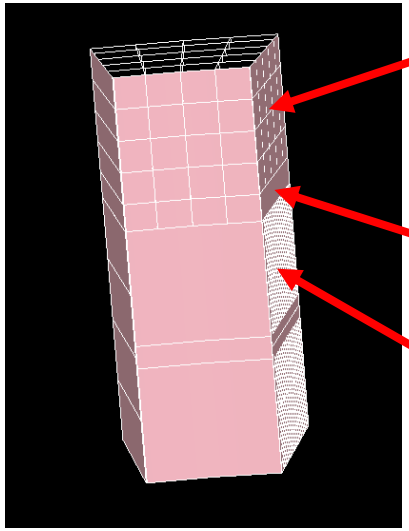
FMA Thermal Requirement

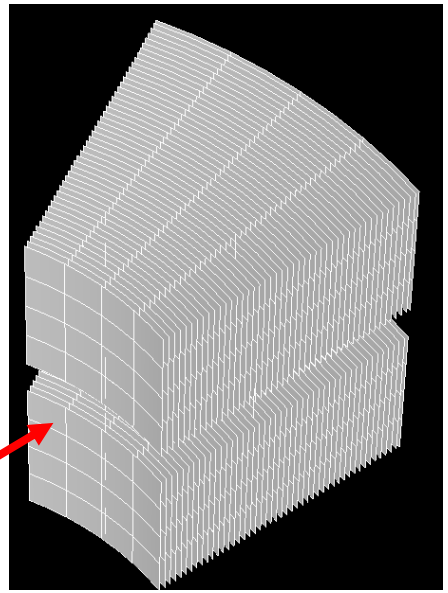
- Mirror segment spatial temperature requirement in operating mode
  - 20°C±1°C
    - 24 outer modules with 206 segments per module
    - 24 middle modules with 230 segments per module
    - 12 inner modules with 286 segments per module
  - ±0.5°C within SXT module
- Mirror segment temporal temperature requirement
  - ±0.1°C temperature stability in operating mode
    - Heater controller tolerance specification
- Survival temperature limits
  - 10°C minimum and 30°C maximum
- Electrically conductive thermal coatings required
- Heater power allocation from Observatory is 1473 W

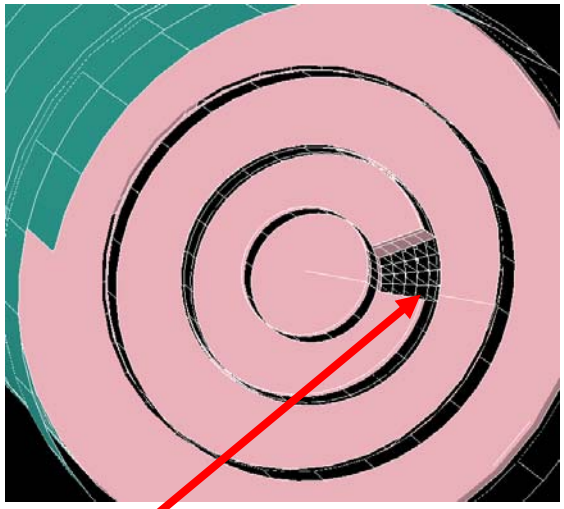
SXT Thermal Design

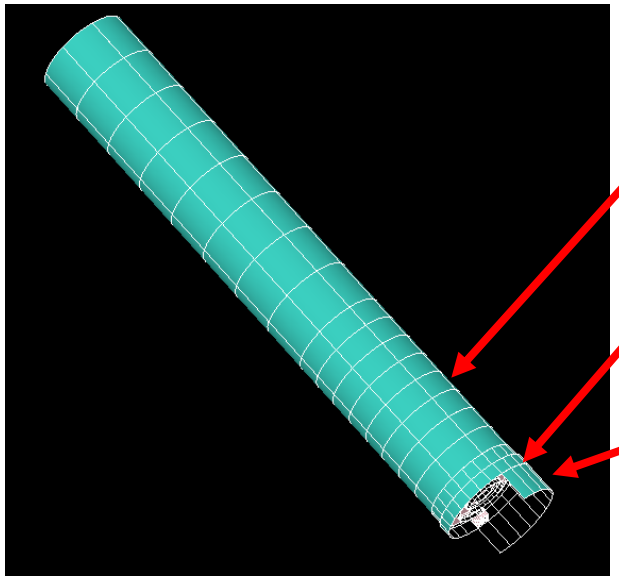
- Active heater control
  - **Multiple heater zones on stray light baffles, module enclosure and section of metering structure adjacent to FMA**
- MLI on exterior of metering structure and, as much as possible, adapter
- Cold-biasing FMA to allow active heater control and minimize heater power
  - **Conductive silver composite coating (low absorptance and high emittance) on adapter MLI outer cover**
    - **GGS WIND and POLAR, and IMAGE LENA flight heritage**
  - **50% conductive silver composite coating and 50% Germanium Kapton (alternate stripes) on metering structure MLI outer cover**
    - **Germanium Kapton has *Swift* BAT flight heritage**
  - **Conductive silver composite coating on sunshade sun side**
- Depth of collimator/stray light baffle affects view of mirror segments to space
  - **Significant parameter to be varied**

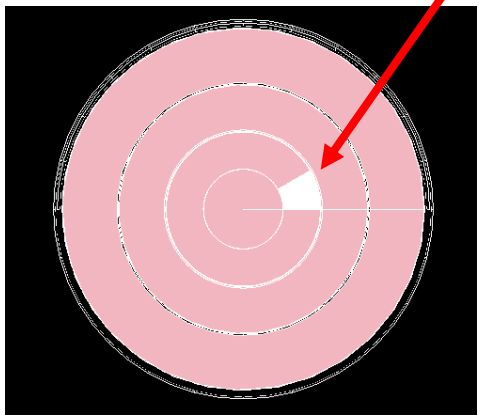
SXT Thermal Modeling / Assumptions

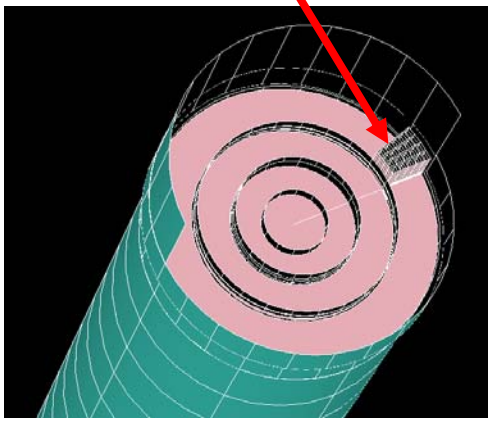












SXT Thermal Modeling / Assumptions

- Each mirror module has its own heater control and is thermally independent of other modules
- Each mirror segment has 16 nodes on each side
- Only one module is included in thermal model at a time for temperature predictions due to very large number of surfaces of all 60 modules and size of radiation couplings
  - Nearly 5 million radiation couplings for one module and file is larger than 300K KB
  - A different model for inner, middle or outer modules
  - Total heater power is calculated for all 60 modules based on number of modules and heater power for each module
- Mirror is thin glass and coating is iridium
  - Very low thermal conductivity (~1 $Wm^{-1}K^{-1}$)
  - Emittance is 0.05 and specular
- Backside of mirror is glass with no coating (high emittance) due to stray light
- Conduction path from mirror segments to module enclosure is very low

SXT Thermal Modeling / Assumptions

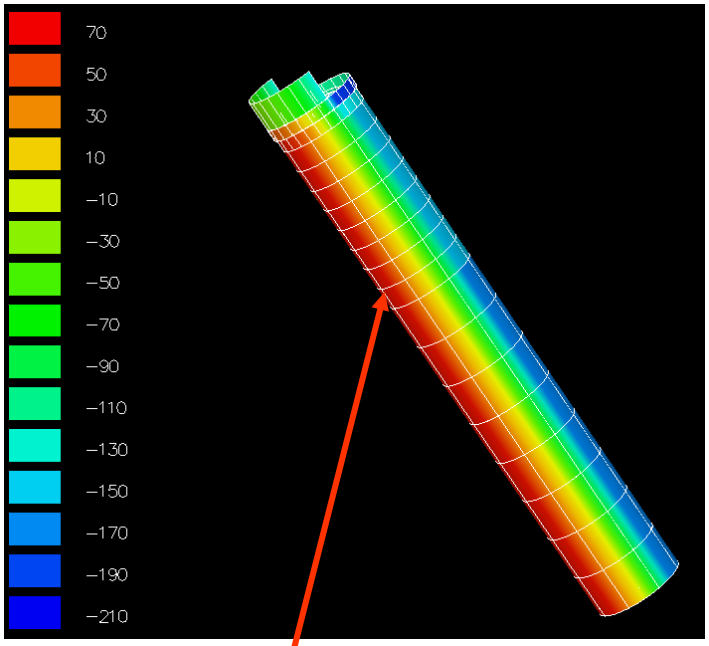
- Pre-collimator has very low thermal conductivity
  - Fiberglass, G-10, etc.
- Interior of metering structure has a high emittance to enhance heat radiation from sun side to anti-sun side
- Anti-sun side of sunshade is black Kapton
- Heater controllers have ±0.1°C tolerances or better

	BOL		EOL (5 Years)	
Coating	Absorptance	Emittance	Absorptance	Emittance
Conductive Silver Composite	0.08	0.60	0.25	0.58
Germanium Kapton	0.45	0.78	0.56	0.76

SXT Thermal Predictions

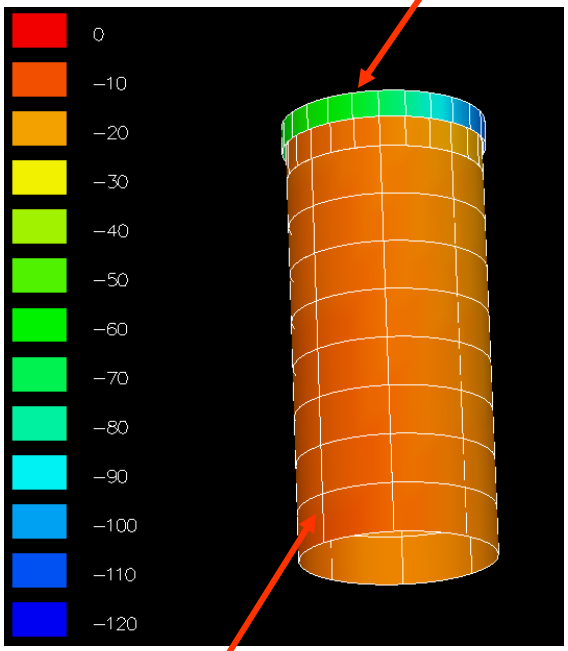
Worst Hot Case, No Active Heater Control, Sufficiently Cold Biased.

Temperature in °C

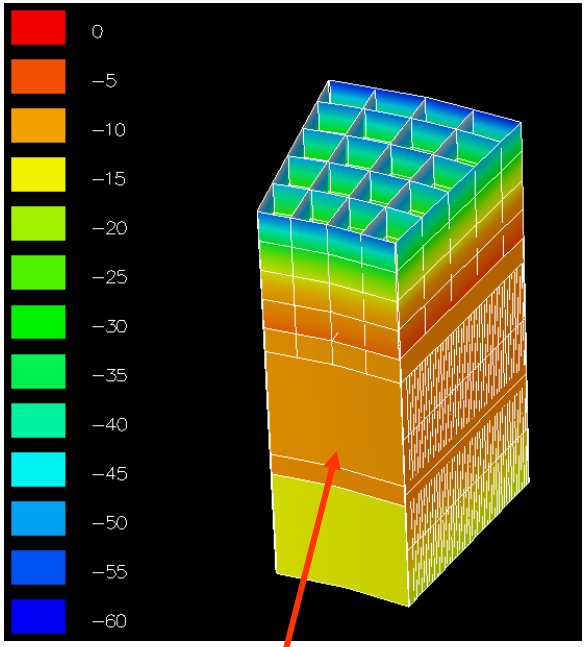


MLI

Adapter



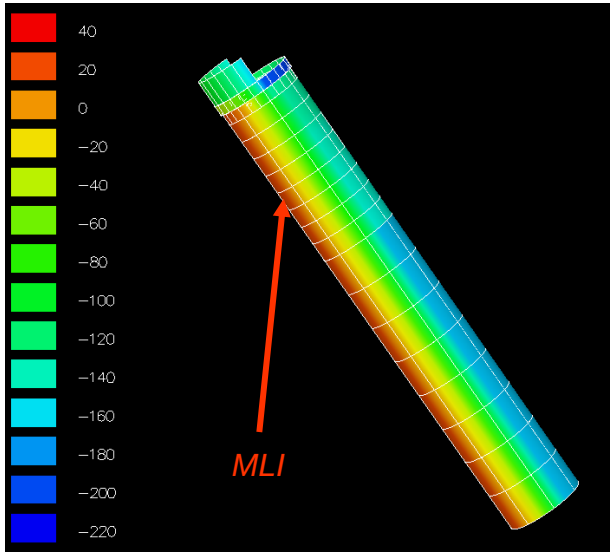
Metering Structure (M55J)

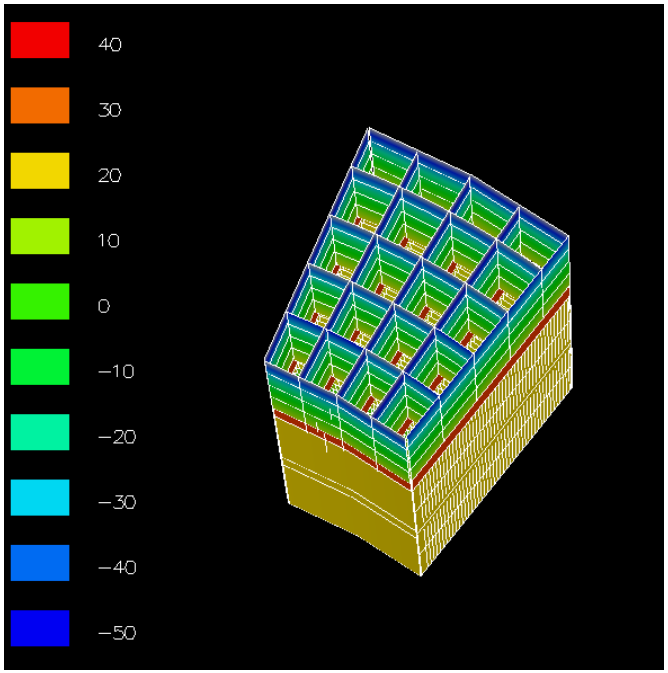


Outer Mirror Module

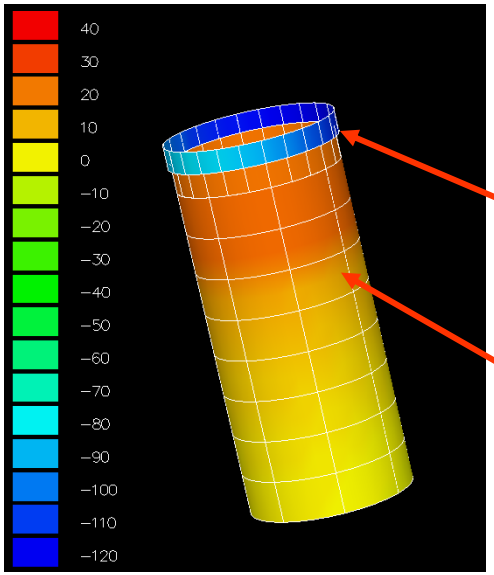
SXT Thermal Predictions

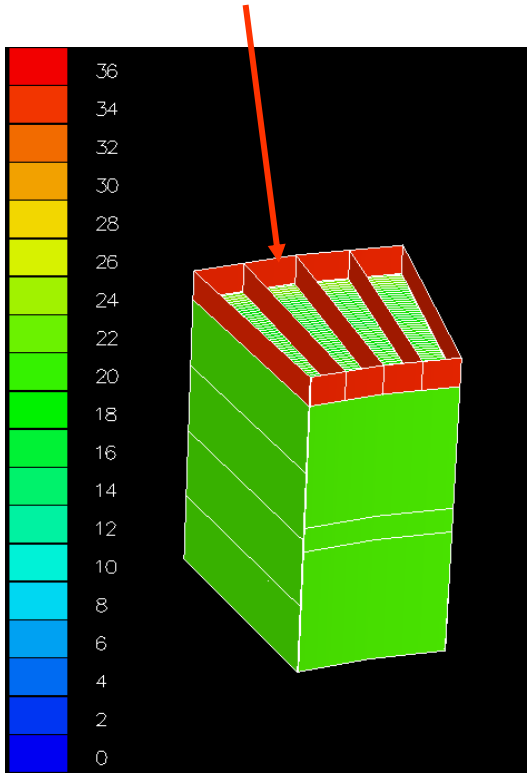
Worst Cold Case, Active Heater Control
Temperature in °C





Outer Module





SXT Heater Power Predictions

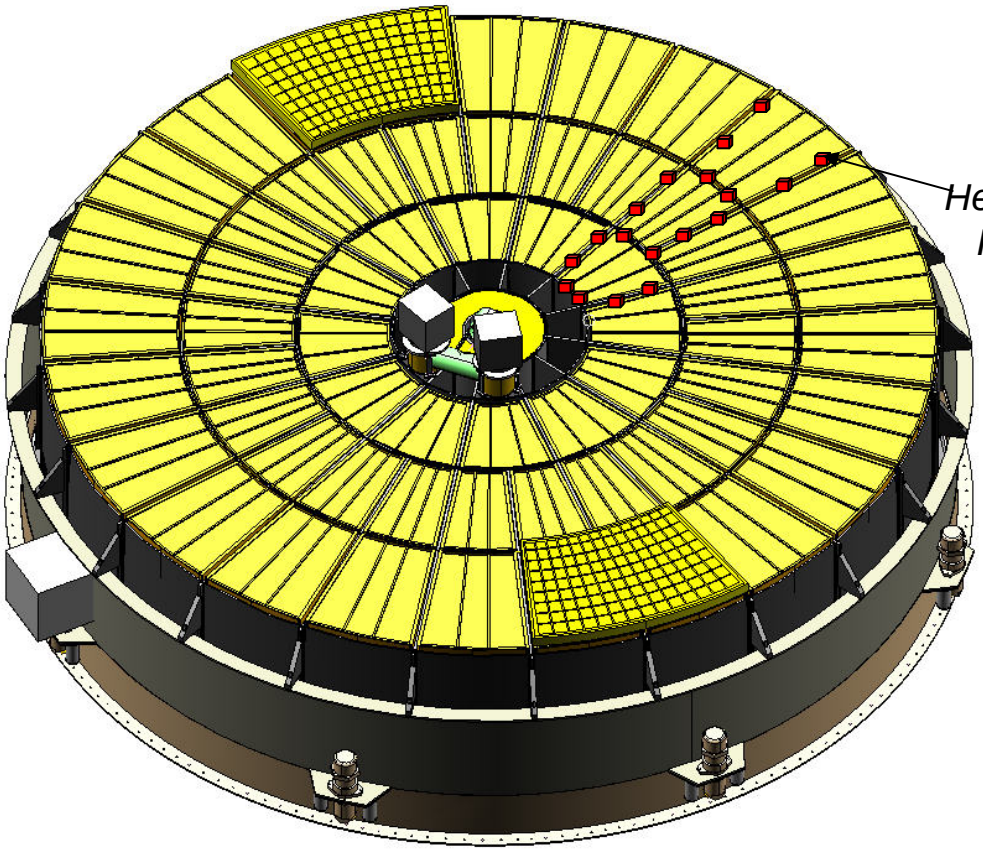
	Heater Power (W)*
Outer Modules	650
Middle Modules	360
Inner Modules	100**
Metering Structure	420
Total	1530

**BOL worst cold case.*
***A thin aluminized Kapton layer on top of stray light baffle. Aluminum side facing optics.*

Approach to Minimize SXT Heater Harness Mass

Distributed Heater Controller Approach:
Use multi-channel and small heater controllers, like those flown on Swift BAT.*
Mount module heater controllers to structure members adjacent to each module.
Mount metering structure heater controllers to metering structure adjacent to heater.

Adjustable set point in flight.
Heater controller set points changed to 12°C in non-operating or safehold Mode. This approach eliminates need for survival heater circuits.



**7.57 cm x 10.48 cm x 2.70 cm and 0.22 kg each. Adjustable set point in flight.*

SXT Heater Controller, Heater and Harness Mass Estimate

	Harness Mass (kg)	Heater Mass (kg)	Thermistor Mass (kg)	Heater Controller* (kg)
Outer Modules	9	14	0.3	40
Middle Modules	6	9	0.2	26
Inner Modules	3	5	0.1	14
Metering Structure	1	9	0.2	5
Subtotal	19	37	0.8	85
Total	142 kg			

Redundancy included.
*Eliminates temperature control boards in RIU box.

Propulsion

Propulsion Subsystem Drivers

- Load Propellant For A ELV Maximum Lift-Off Mass = 6425 kg
- Provide A Thruster Suite For Six Degrees Of Freedom
- Provide Max Thruster Arm For Thruster Couples During Reaction Wheel Offload
- Size Prop System for Ten Year Mission Life
  - Consider possible Tank accommodation for 25 year Mission
- Design with Flight Heritage Components
  - Minimizes qualification cost and flight/schedule risks
  - No customization for mass saving
- Design For Single Fault Tolerance (selective redundancy)
  - No credible single point failures (GSFC-STD-1000, Rule 1.05)
  - Dual fault tolerant where required by range safety
- Minimize Contamination to Optically Sensitive Surfaces
  - Locate thrusters to minimize S/C plume impinge and provide no direct line of sight between thruster nozzles and optically surfaces

Key Ops Parameters

- Stationkeeping once every 21 days
  - After 21 day undisturbed orbit determination arc (as required by DSN) has been completed
- Pseudo-continuous Solar Pressure offloading
  - 0.11 s burn every 18 minutes: 0.165 arcsec deviation
  - 300,000 Thruster Firings over 10 Years (once per 18 min)
    - Voyager had 500,000 burns from single thruster, using same thruster
  - Total amount of monopropellant: 16.5 kg

Propulsion Subsystem Mission Delta-V Profile

DELTA V BUDGET FOR 10 YEARS				
	Estimate	ACS Tax	Contingency	Subtotal
Launch Window	10 m/sec	5%	0%	11 m/sec
ELV Dispersion Correction	20 m/sec	5%	0%	21 m/sec
Mid-Course Correction	10 m/sec	5%	5%	11 m/sec
Orbit Lowering Maneuver	0 m/sec	5%	0%	0 m/sec
L2 Stationkeeping for 10 years	40 m/sec	5%	5%	44 m/sec
Momentum Management for 10 years	9.8 m/sec	0%	5%	10 m/sec
De-orbit	1 m/sec	5%	5%	1 m/sec
Total Equivalent Delta V				98 m/sec

ALLOCATION PROPELLANT BUDGET	
	Allocation
Allocation Dry Mass	5850.7 kg
Prop Mass (use equivalent Isp =275)	216.1 kg
5% Ullage and Residual	10.8 kg
Allocated Propellant Mass	226.9 kg

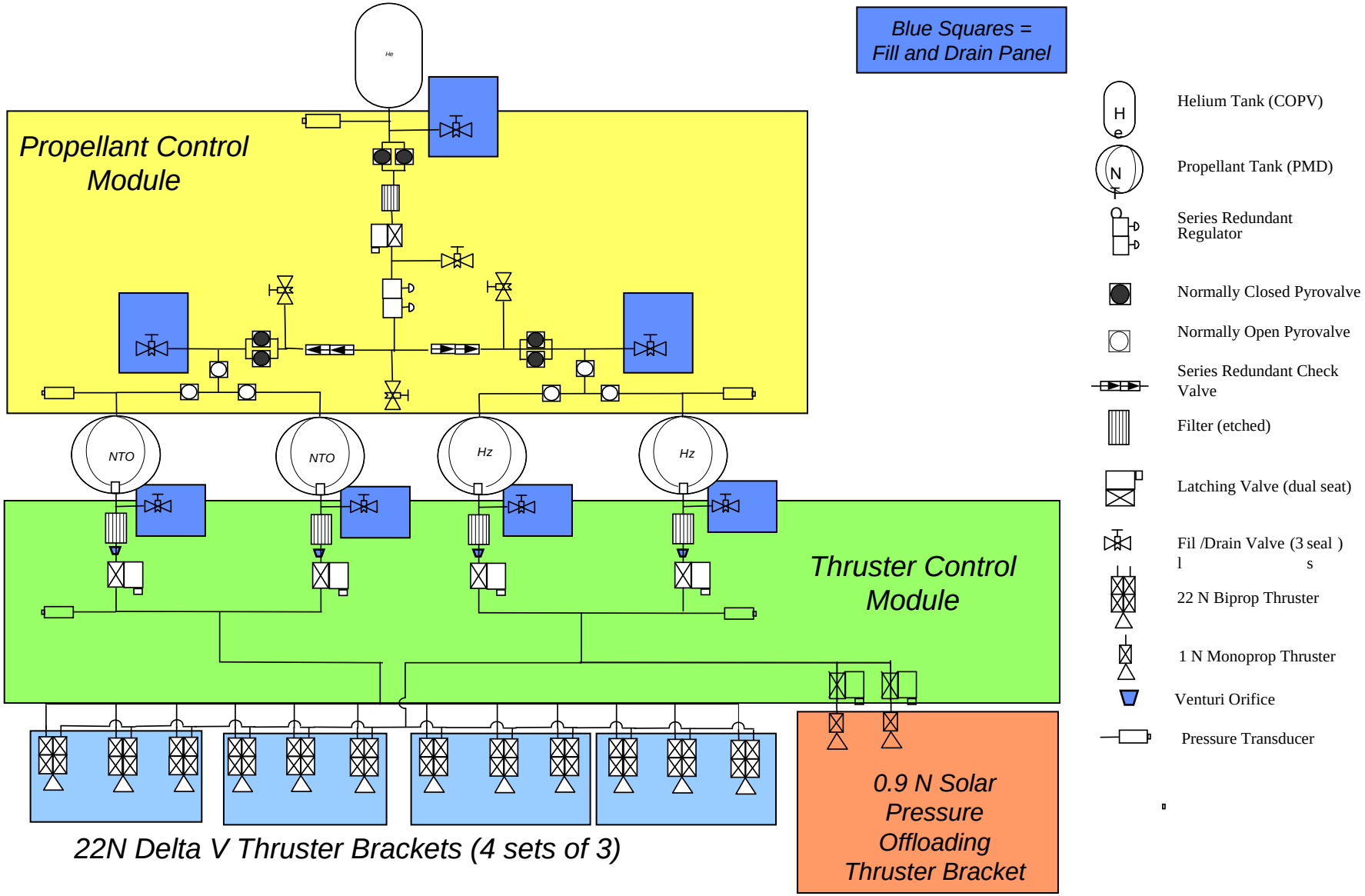
Propellant Specific Impulse

Isp = 275.5 sec (MMH) Bi-prop

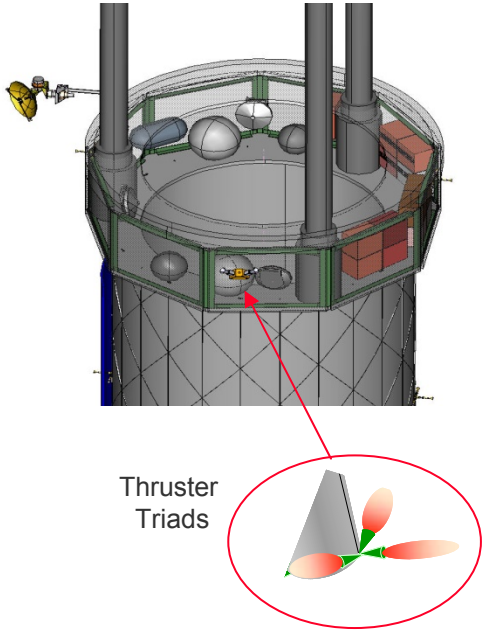
Propulsion Subsystem Description

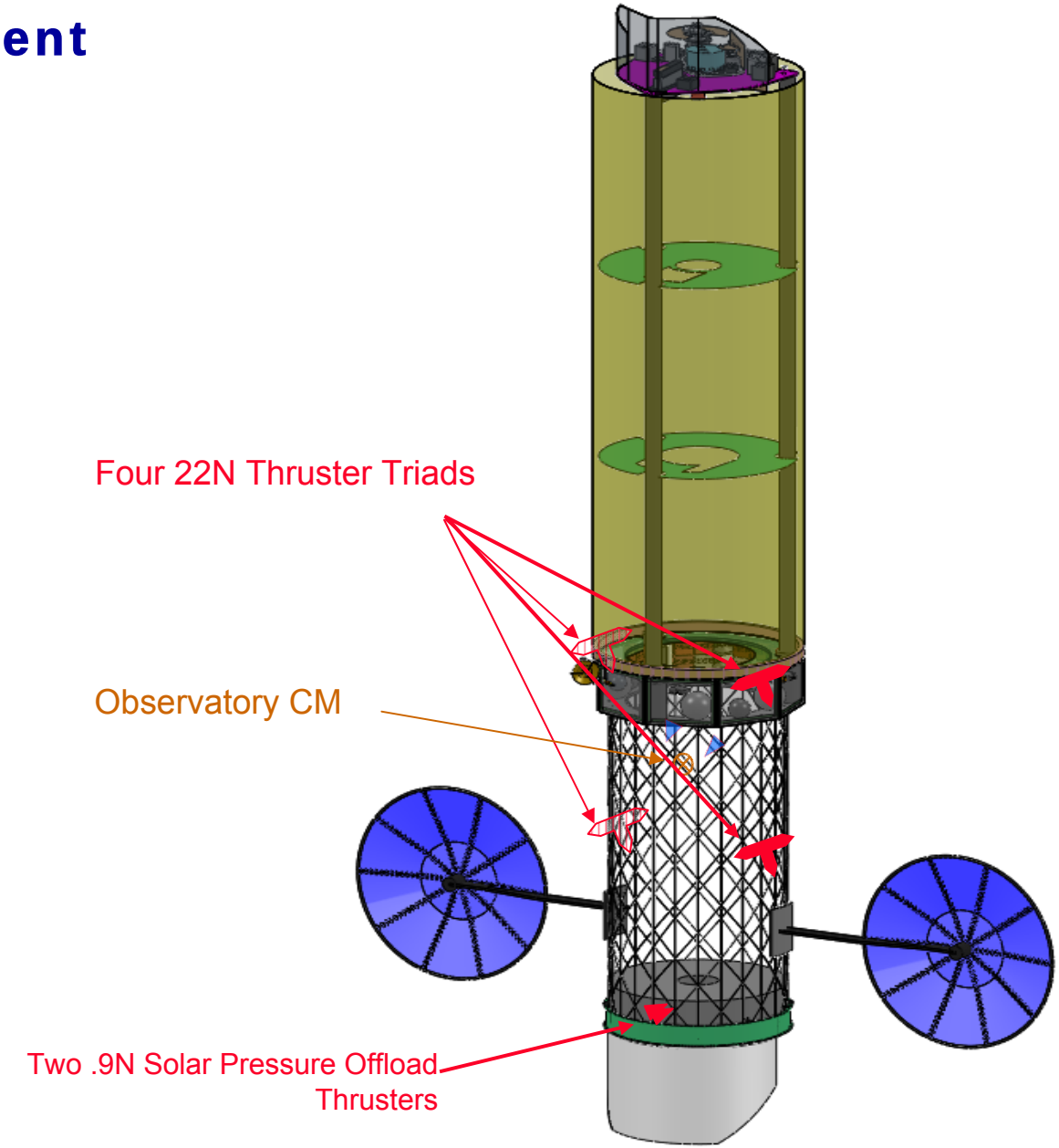
- Pressure Regulated, NTO/Hz, Bipropellant Propulsion Subsystem
  - Total Propellant Mass Load = 230 kg
  - Mass Mixture Ratio = 0.86
- Series Redundant He Regulator With High Pressure Isolation Latch Valve For Long Life Operation
- Twelve (12), Single String, 22N Biprop ACS And Station Keeping Thrusters
- Redundant .9 N Thrusters for Solar Pressure Offloading
- One (1) COPV Titanium He Tank
- Monolithic Titanium NTO & Hz Tanks (2 each)
- Propellant Manifolds & Components Are All Titanium
- Venturi Orifices Below Fuel Filters To Minimize Water Hammer Surge Pressure During Thruster Priming
  - Required by Goddard GOLD Rules
  - Fuel flight manifold test simulators required to flow test Venturi orifice surge & flow loss performance

Propulsion Subsystem Block Diagram w/ Modules



Thruster Placement





22N Thrusters Burn Times and Accelerations

- Largest burn is ELV Dispersion Correction at (abs. worst case of 40 m/s – see note on PMD)
- Nominal case: 4 ea. 22N Thrusters operating w. zero cosine loss: 88N Thrust force
- Observatory Mass used: 5930 kg
- Burn time is 2696 sec
  - t = m*v / F >>> 5930kg * 40m/s / 88N = 2696 sec
- Acceleration: 1.5 mili-g
  - a = F/m >>> 88N / 5930kg = 0.015 m/s2

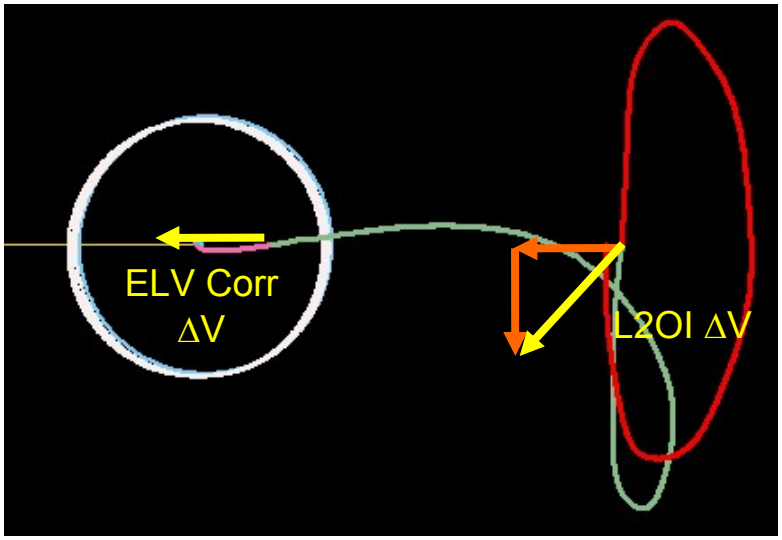
Solar Pressure Offload by 0.9 N Thruster Firing

- Attitude Deviation versus Pulse Length
  - 0.11 s burn every 18 minutes: 0.165 arcsec deviation
- Number of 0.11 s Thruster Firings:
  - 300,000 over 10 Years (once per 18 min)
    - Voyager had 500,000 burns from single thruster, using same thruster
  - Total amount of propellant: 15 kg
- Assumes IXO config with two 3.35 m dia Circular Ultraflex Solar Arrays

Biprop PMD Considerations

- Bidirectional Biprop propellant management devices
- Unidirectional PMDs could limit the execution of large maneuvers into only one single direction (to force propellant out of the tank)
- This situation would require the following accommodations
  - The tanks need to be aligned such that thrusting towards the Sun is the primary direction
  - The launch will be biased to be "hot" such that ±3σ dispersion correction will be towards the Sun
  - The vector sum of the L2OI ΔV will be towards the Sun
- L2 stationkeeping and ΔH maneuvers must be executed within limits of PMD reservoir

- If IXO would be limited by PMD for, that would double the ELV Dispersion Correction ΔV (40 m/s); if If not, then this ΔV line item is 20 m/s.



Propulsion Parts List w/ Heritage and TRL

Component	Vendor	Model P/N	Lead Times (mo)	Description	Performance Spec	Interfaces	Qty Used (ea.)	Unit Mass (kg)	Total Mass (kg)	Unit Size/ Volume (m)	Unit Cost ($k)	TRL	Heritage
Hz Tank	PSI	80364-1	12	Ti PMD tank	Op Press 400 psig (27.58 bar)	Transition tube outlet, Ti inlet	2	5.67	11.34	Spherical 22.14 in (562mm)	300	9	INMARSAT-3
NTO Tank	PSI	80304-1	12	Ti PMD tank	Op Press 400 psig (27.58 bar)	Transition tube outlet, Ti inlet	2	3.86	7.71	Spherical 19.03 in (483mm)	300	9	SPACENET
He Tank	PSI	80412-1	14	Composite Over-wrapped Pressurant Vessel	Op Press 2,176 psig (150.03 bar)	Ti outlet and inlet'	1	6.99	6.99	12.8''IDx27.5'' Long (325x698.5 mm)	100	9	ETS8 Xenon
22N Hz/NTO Thruster	AMPAC	DST-11H	12	ISP >300 Fee press 80-400 psia	22N (5 lb) Hz/NTO	Ti tube, mounting flange	12	0.74	8.88	10in (25.4cm) long by 3in (7.62cm) dia	90	8	OSC Wild Geese
1N Hz Thruster	Aerojet	MR-103C	8	ISP 224-209s Feed press 400-90 pia (27.6-6.2 bar)	1N (0.2 lbf) Hz, 410,000 pulses	Mounting flanges	2	0.33	0.66	5.82in (14.8cm) x 1.35in (3.4cm) dia	75	9	DS-1, Skynet 4, ADEOS3, MSTI
3/8'', dual coil, LP Latch Valve	Vacco	V1E10362-01	8	5,000 cycle life	300-600 psi (20.7-41.4 bar)	3/8'' Ti, connector	6	0.73	2.90	6.63in (16.8cm) x 2.44in (6.2cm) footprint	30	9	MUSES-C, ASTRO-F, classified
3/8'', dual coil, HP Latch Valve	Vacco	V1E10560-01	8	5,000 cycle life	4500 psia (310 bar) operating pressure	3/8'' Ti, connector	1	0.73	0.73	6.63in (16.8cm) x 2.44in (6.2cm) footprint	30	9	MUSES-C, ASTRO-F, classified
Pyro Valves (NO/NC)	Conax	TBD	8	Zero leak metal seal	Op press varies	Ti tube	12	0.16	1.91	~4in (10.2cm) long	15	9	Atlas, Rosetta, WINDS, many more
Check Valve (dual seat)	Vacco	V0E10495-01	8	1000 operation cycles	Proof 1000 psi (68.9 bar)	Ti tube	2	0.11	0.23	6.4x2.12in (16.3x5.4 cm) footprint	25	9	Many programs, first flew for LM in 1994

Total Mass is the total DRY mass, propellant not included.

Cost does not include spares or NRE

Propulsion Parts List w/ Heritage and TRL

Component	Vendor	Model P/N	Lead Times (mo)	Description	Performance Spec	Interfaces	Qty Used (ea.)	Unit Mass (kg)	Total Mass (kg)	Unit Size/ Volume (m)	Unit Cost ($k)	TRL	Heritage
He Regulator (Series Redundant)	Mu	Inlet 5000 to 360 psig	10	Set regulated output press between	Accuracy of +/-2.5% reg outlet pressure	Connector , Ti tube	1	1.25	1.25	2.75in (7cm) x 2.5in (6.4cm) dia	100	9	Mars Odyssey, Mars Orbiter, Cluster II, Messenger
HP Filters (10µ)	Vacco	F1D10286-01	9	10 micron filtration	Op press 4200 psig (290 bar)	Ti tube interface	1	0.11	0.11	4.1in (10.4cm) Long, 1.12in (2.8cm) dia.	10	9	HS-601, HS-702, Cassini, Chandra, many other S/C
LP Filters (10µ)	Vacco	F1D10559-01	9	10 micron filtration	Op press 400 psig (27.58 bar)	Ti tube interface	4	0.30	1.20	7.85in (19.9cm) Long 1.75in (4.3cm) dia	10	9	HS-601, HS-702, Cassini, Chandra, many other S/C
Fill/Drain Valves	Vacco	TBD	9	Load fuel and pressurant as well as test ports	3 seals	Ti tube interface, mounting flanges	11	0.11	1.25	~5 in (12.7cm) long by ~1in (2.54cm) dia	10	9	Many flight programs
Pressure Transducer	Tabor	TBD	10	Reads in voltage the pressure of the tanks	Ranges 0-580 psia (0-40 bar) and 1-4200 psia (0-280 bar)	Ti tube, Connector	5	0.27	1.36	~6 in (15.24cm) long by ~1in (2.54cm) dia	15	9	X-34, ASTRIUM, NEXT
Venturi Orifices	Fox	TBD	4	Eliminate effects of water hammer	As needed	Ti	4	0.05	0.20	3/8'' dia x 1''	2	9	SDO, LRO, many other S/C
Manifold, etc.	TBD	TBD	3	Tubes, manifold stands, etc	As needed	Varies	1	6.81	6.81	TBD	100	9	Many S/C
							TOTAL MASS		**53.3**		**$3.41 M**	**TOTAL COST**	

Total Mass is the total DRY mass, propellant not included.

Cost does not include spares or NRE

Propulsion Verification Matrix

I&T Phase	Verif. Desc. (Requirement)	Assy Level	Model	Verif. Method	Level	Facility	GSE	Simulators	Comments
Phase D-1 Subsystem	LP Thruster Leak Checks	Component	F	T	Accept	Small Subsystem Cleanroom	Pressure regulator, Thruster Nozzle Plugs	none	
Phase D-1 Subsystem	Thruster Manifolds Proof/Leak Test	Subsystem	F	T	Accept	IXO Obs Cleanroom	Pressure regulator	none	
Phase D-1 Subsystem	Thruster/Valve Leak Checks	Subsystem	F	T	Accept	IXO Obs Cleanroom	Pressure regulator, Helium Mass Spectrometer	none	
Phase D-1 Subsystem	Subsystem Proof Test	Subsystem	F	T	Accept	IXO Obs Cleanroom	Pressure regulator	none	Verify workmanship of welded system; prove all welds not previously proven
Phase D-1 Subsystem	Subsystem External Leak Test	Subsystem	F	T	Accept	IXO Obs Cleanroom	Pressure regulator, Helium Mass Spectrometer	none	Verify leak-free welds
Phase D-1 Subsystem	Subsystem Internal Leak Tests	Subsystem	F	T	Accept	IXO Obs Cleanroom	Pressure regulator, Micropipette, EGSE	none	Verify leak-free latch valve, fill/drain valve, and thruster seats
Phase D-1 Subsystem	Electrical Functional Tests	Subsystem	F	T	Accept	IXO Obs Cleanroom	Pressure regulator, EGSE	none	Verify electrical parameters of electrical components
Phase D-1 Subsystem	Gas-Flow Impedance Testing	Subsystem	F	T	Accept	IXO Obs Cleanroom	Thruster nozzle plugs, flow panel, pressure regulator	none	Verify flowrate through each thruster at known pressure differential
Phase D-1 S/C	Prop/Avionics Command Verification	S/C Bus	F	T	Accept	IXO Obs Cleanroom	Thermocouples	none	Verify commands from avionics, Actuate all latch valve coils, all thruster valves, cat-bed heater services
Phase D-1 S/C	S/C EMI/EMC Testing	S/C Bus	F	T	Qual	EMI Facility		none	Monitor propulsion status
Phase D-1 S/C	Thruster Alignment	S/C Bus	F	T	Accept	IXO Obs Cleanroom	Theodolites, etc	none	Pre-vibration measurement of angular misalignement and Cartesian coordinates for all thrusters
Phase D-1 S/C	S/C Vibration & Accoustics Testing	S/C Bus	F	T	Qual	Vibe/Accoustic Chamber	Mass Simulators for all Flight Hware items and fuel	none	Monitor propulsion status
Phase D-1 S/C	Subsystem Internal Leak Tests	S/C Bus	F	T	Accept	IXO Obs Cleanroom	Pressure regulator, Micropipette, EGSE	none	Verify leak-free latch valve, fill/drain valve, and thruster seats
Phase D-1 S/C	Gas-Flow Impedance Testing	S/C Bus	F	T	Accept	IXO Obs Cleanroom	Thruster nozzle plugs, flow panel, pressure regulator	none	Verify flowrate through each thruster at known pressure differential
Phase D-1 S/C	Thruster Alignment	S/C Bus	F	T	Accept	IXO Obs Cleanroom	Theodolites, etc	none	Pre-vibration measurement of angular misalignement and Cartesian coordinates for all thrusters
Phase D-1 S/C	S/C Thermal Balance Test	S/C Bus	F	T	Qual	Thermal Vacuum Chamber	Thermocouples	none	Propulsion loopbacks installed, verify commands from avionics, Actuate all latch valve coils, all thruster valves, catbed heater services

EPS

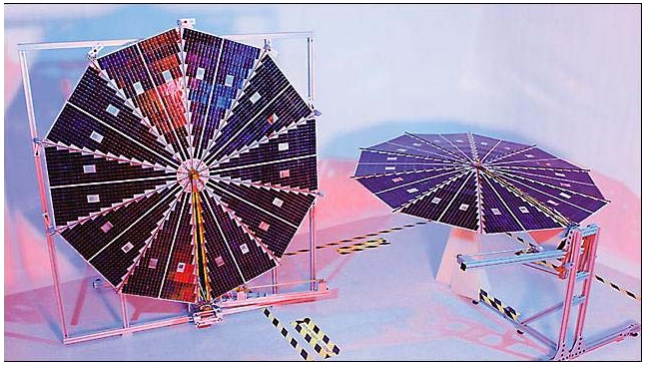
Summary

EPS Sizing:	**Sized for 10 years**
Total Output	**6600 W BOL max, 5200 W EOL min (10 yrs - 20% decay)**
Solar Arrays:	**UltraFlex Solar Array (272 w/m2 per ATK): 3900 W (BOL)**
	Total S/A area populated by solar cells: 14.3 m2
	Total area available : 18 m2
	Body mounted array: 2700 W (BOL)
	Total surface area: 11.4 m^2
Battery:	**1400 Wh (50 Ah) LiIon battery**
	Cell by-pass switches, w/ trickle charger
Instruments and S/C:	**28 VDC regulated PSE power**
FMA Thermal:	**Unregulated power from EPS bus.**
	Body mounted array to provide baseline (constant peak power) and run full on at all times from begging of life (BOL) to end of life (EOL).

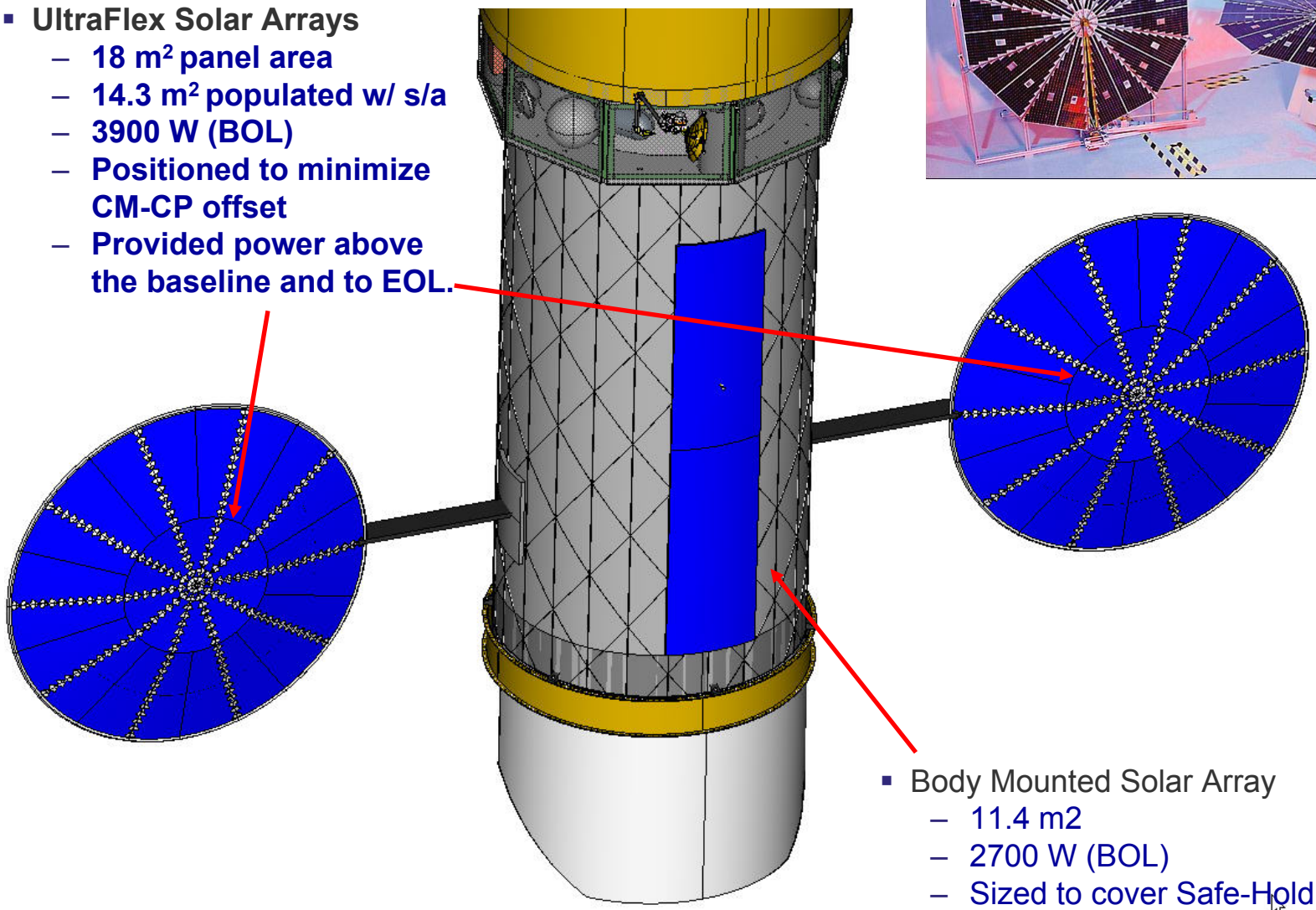
EPS Configuration Overview

- Body mounted solar array
  - 11.4 m2 body mounted solar array: 2700 W (BOL)
  - All survival heaters wired exclusively to Body Mounted Array
    - Allows for Observatory Safe-Mode of indefinite duration even right after LV separation (before deploying Ultraflex arrays)
    - All FMA Heaters also wired to Body Mounted array, but bypassing regulators (see "FMA Temp Control Electrical Block Diagram" slide)
  - During normal mission modes, all of the body mounted strings will provide their max capacity power to the bus. This provides as constant thermal load on the shell of the spacecraft as possible.
- Two UltraFlex solar arrays contribute to main Observatory power
  - 2 ea 7.15 m2 Solar Arrays for 14.3 m2 total area (at 272 W/m2 per ATK); 3900 W (BOL)
    - Arrays total wing size about 3.4 m diameter (9.0 m2 per wing)
    - Only partially populated w/ cells, rest of the area used as a Solar Sail to minimize CM-CP offset
    - Array mounts positioned on Fixed Metering Structure
  - S/A output routed to PSE, regulated to 28VDC to power Observatory
  - The UltraFlex arrays will provide the difference between the load demand and the capability of the Body Mounted solar array. This array will make up the difference as the spacecraft goes to end of life (EOL) both to compensate for the degradation of the body mounted array and for any increase in thermal FMA EOL power increases.
- 1400 Wh battery sized to carry observatory safe-hold mode for at least 30 minutes even without sun. Not needed during any of the foreseen mission modes, only during entirely unforeseen events, since at all times during the entire mission the s/a's point at the sun
- Power System Electronics has built in redundancy

S/A Layout

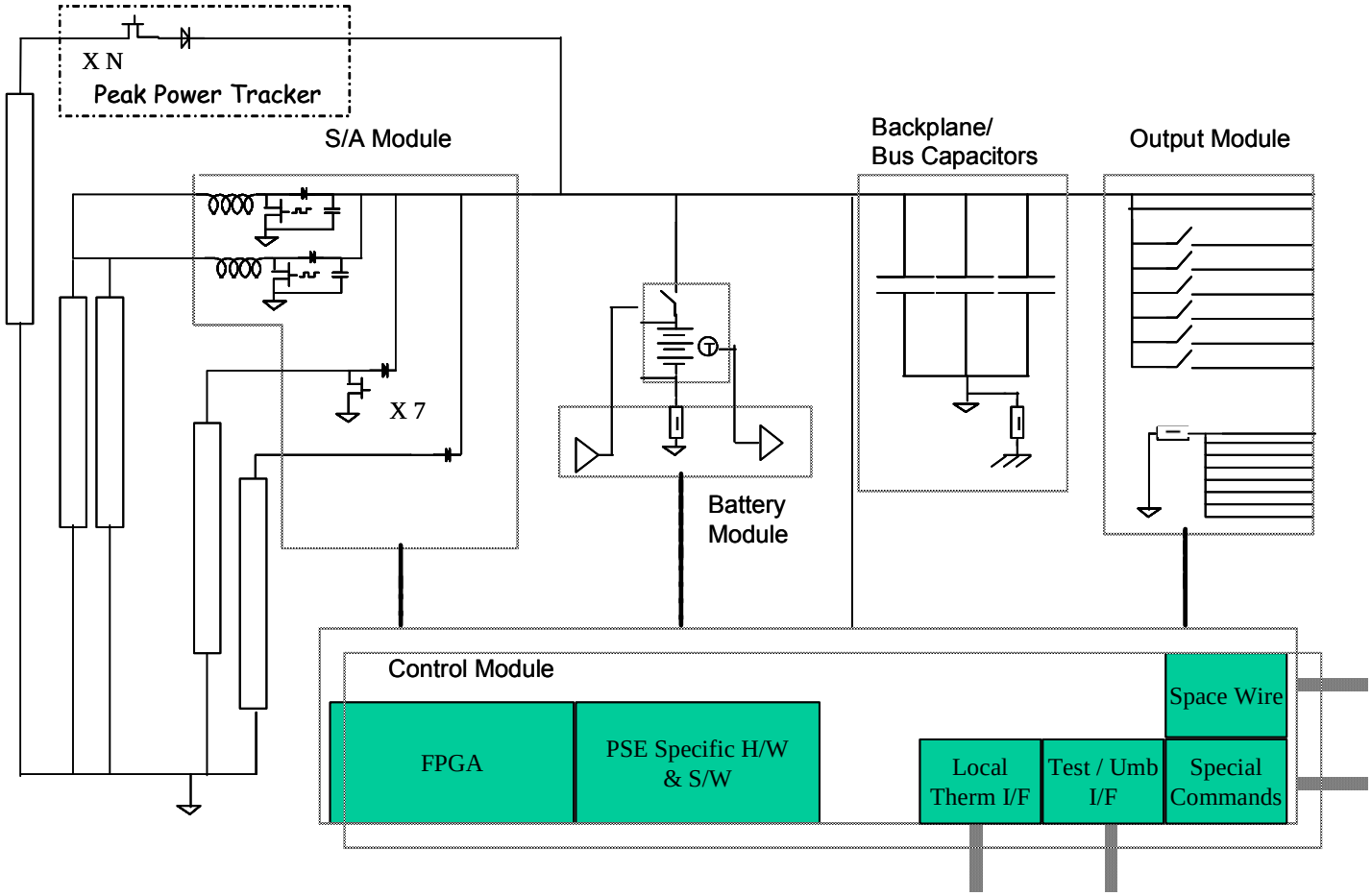


- UltraFlex Solar Arrays
  - 18 m^2 panel area
  - 14.3 m^2 populated w/ s/a
  - 3900 W (BOL)
  - Positioned to minimize CM-CP offset
  - Provided power above the baseline and to EOL.

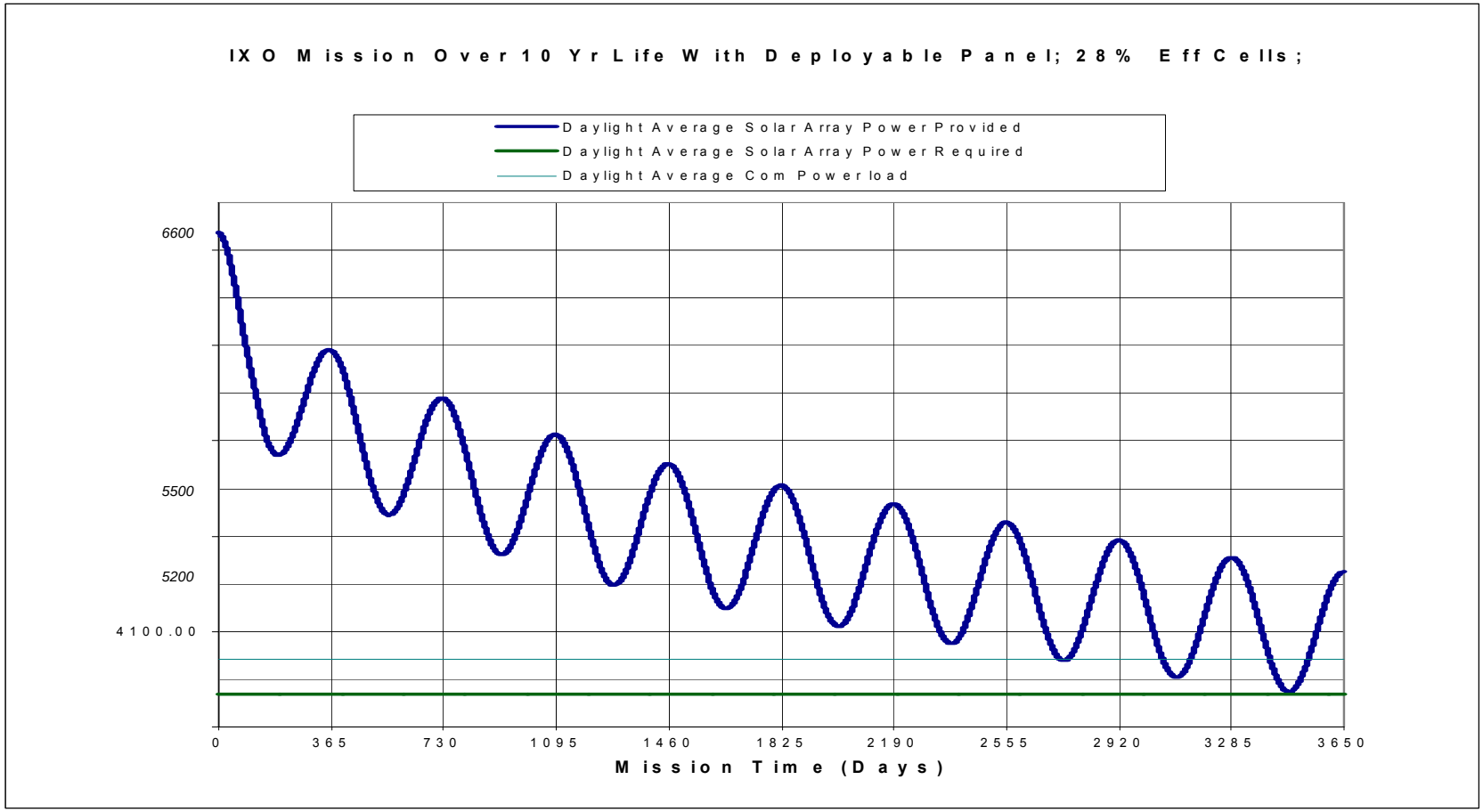


- Body Mounted Solar Array
  - 11.4 m2
  - 2700 W (BOL)
  - Sized to cover Safe-Hold Mode
  - Provides Baseline constant power

EPS Electrical Block Diagram



Typical L2 10 Year Decay of S/A Output



Ultraflex Array Properties

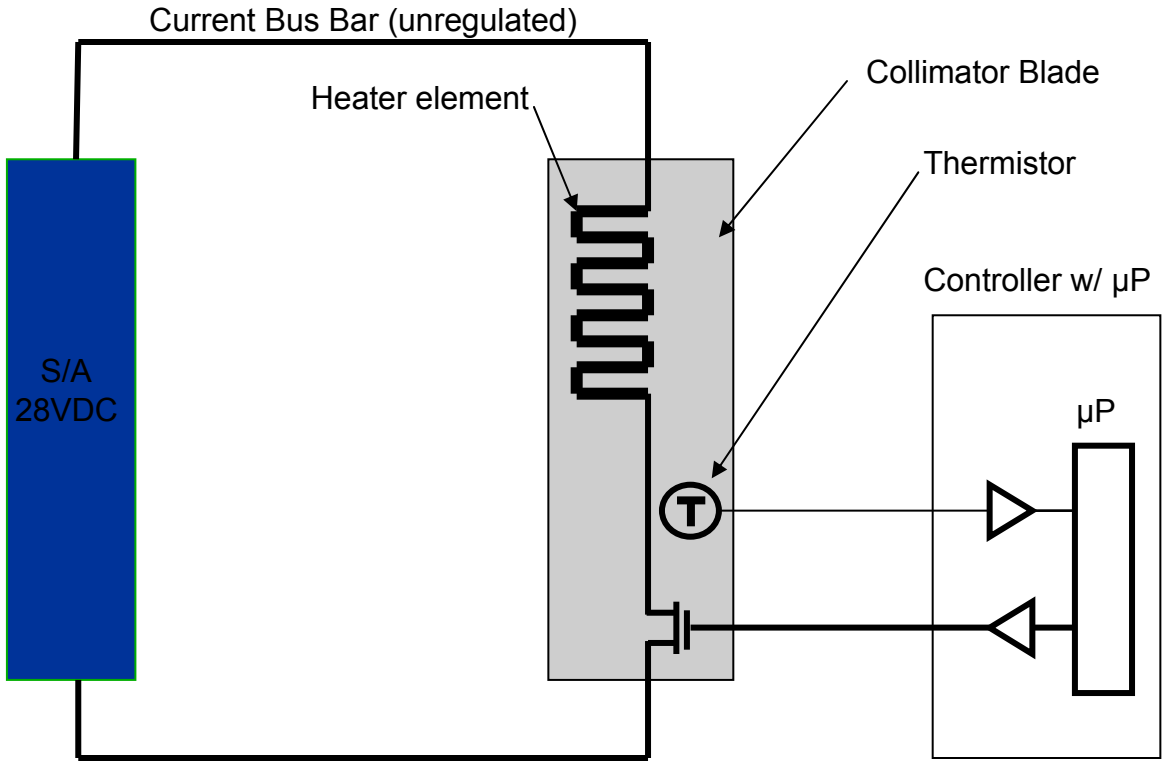
	BOL Values
Specific power	***156 W/kg***
Power / unit area	272 W/m^2
Area density	1.75 kg/m^2

- **Configuration:**
  - **Wing size 3.4 m diameter (7.0 m2 per wing)**
    - **7.15 m2 active cell area per wing, 14.3 m2 total: 3900 W BOL**
  - **Array weight**
    - **Two wings fully populated w/ 18 m2 of s/a's: 29.3 kg (assumes "typ." launch loads)**
    - **Two wings partially populated w/ 14.3 m2 of s/a's: 27.3 kg**

- **XTJ GaInP2/GaAs/Ge solar cells, 110 micron thick**
  - **29.3% min. average cell efficiency**
  - **String length: 16 cells; 80 strings per wing; 1280 cells per wing**
  - **Net string voltage, BOL: 30.5 Volts (for >28V EOL)**
  - **Voc 2.655 V; Jsc 18.10 mA/cm2; Vmp 2.33 V; Jmp 17.45 mA/cm2;**
  - **Fill Factor 84.5%**
  - **4-mil CMG covers**

FMA Temp Control Electrical Block Diagram

- FMA Heater power is not voltage regulated (to increase efficiency)
- Control system regulates current directly on Temperature



SXT Heater Power Predictions

	Heater Power (W)*
Outer Modules	650
Middle Modules	360
Inner Modules	100**
Metering Structure	420
Total	1530

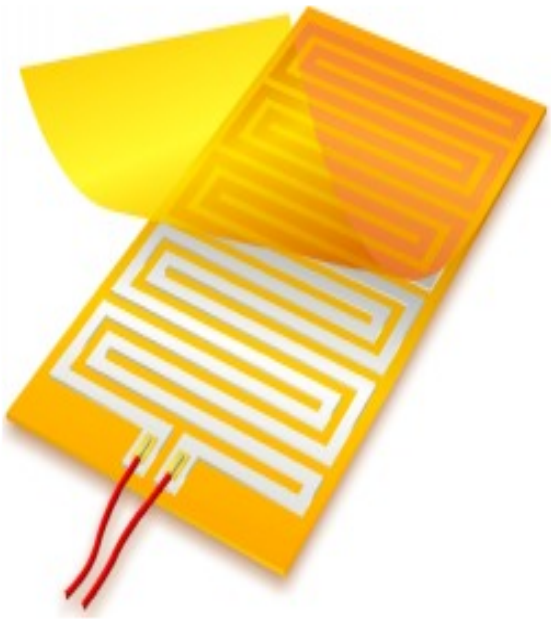
**BOL worst cold case.*
***A thin aluminized Kapton layer on top of stray light baffle. Aluminum side facing optics.*

FMA Temp Control Minco Kapton Foil Heaters

- Shaped to the precise size of the collimator blades for uniform (or even shaped!) heat distribution
- Custom shaping, integrated connector terminations and integrated thermistors simplify harnessing
- Minco Kapton Foil Heaters flew numerous NASA missions

Thermofoil™ Heaters

Thermofoil™ Solutions for Heating



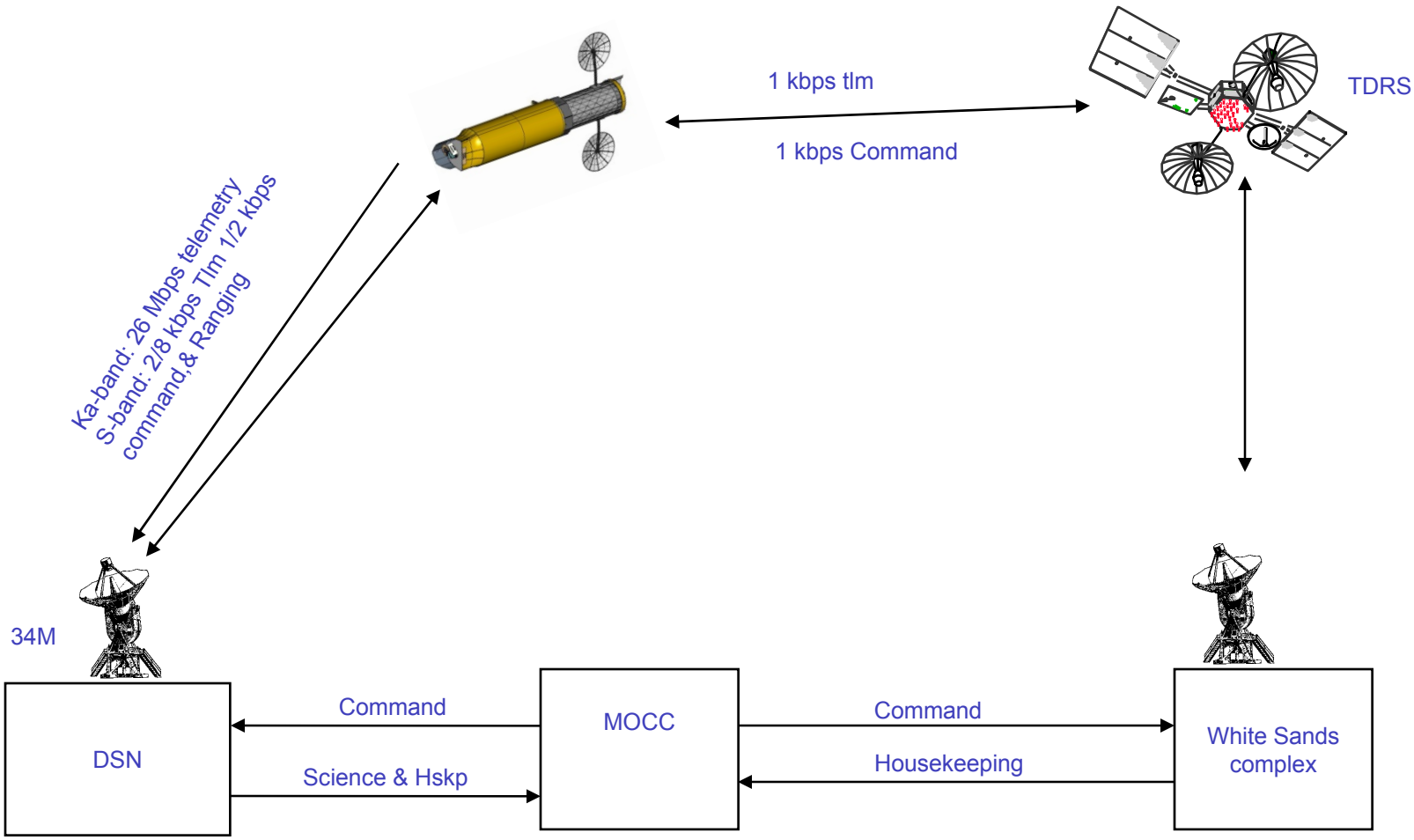
Thermofoil™ heaters are thin, flexible heating elements consisting of an etched foil resistive element laminated between layers of flexible insulation. Since their introduction by Minco over 45 years ago, Thermofoil™ heaters have demonstrated significant advantages over conventional electric heaters:

RF Comm

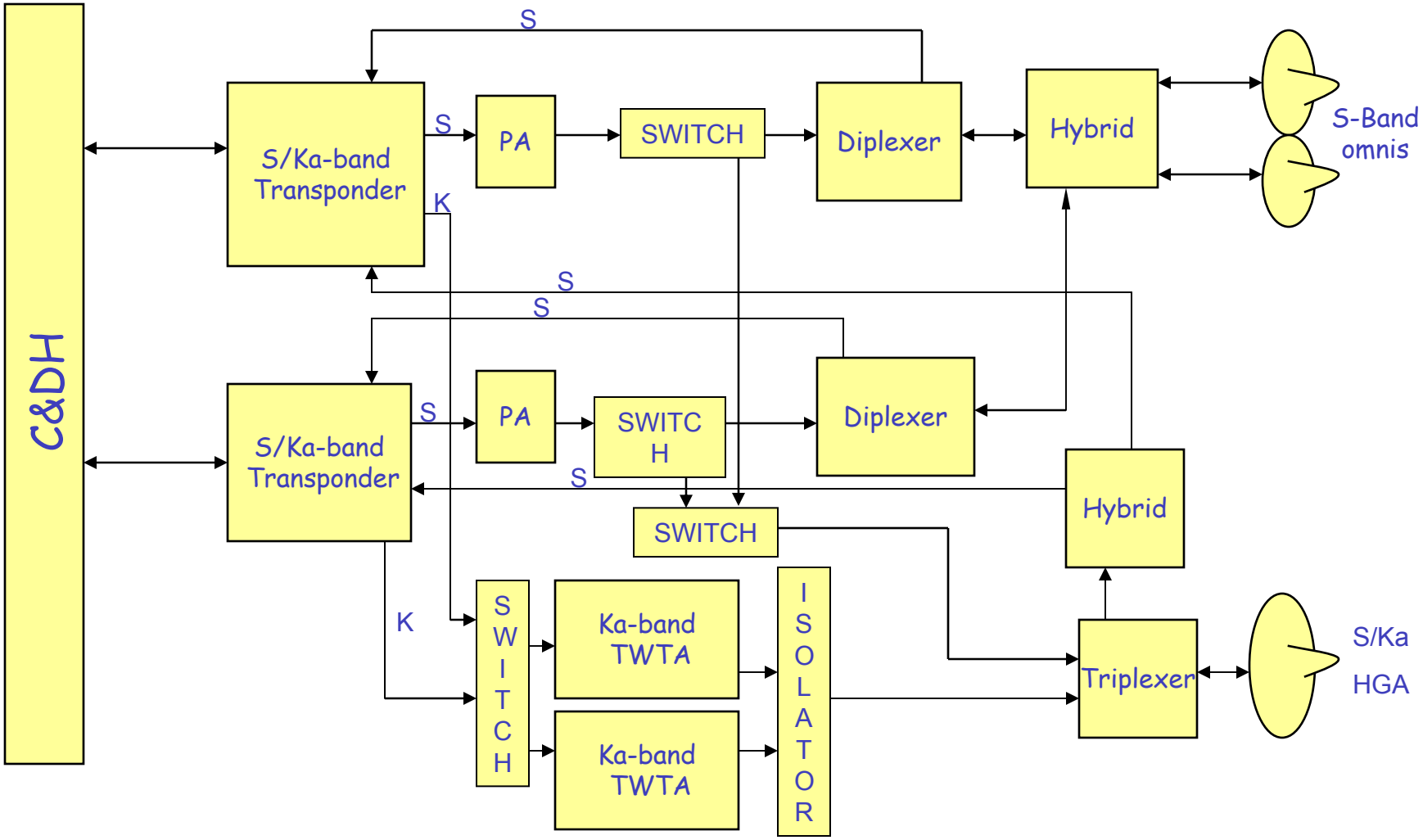
Overview

- Ka-Band for science and data dumps via 0.7 m HGA to DSN 34 meter
  - Data dumps at 26 Mbps
  - One 30 minute contact required
- S-Band TT&C via 0.7 m HGA to DSN 34 meter
  - 2 kbps command
  - 8 kbps telemetry
- S-Band TT&C via omni to DSN 34 meter
  - 1 kbps command
  - 2 kbps telemetry
- Ranging for orbit determination
- S-Band thru TDRSS for launch and LEO critical events
  - 1 kbps command
  - 1 kbps telemetry
- CCSDS
- Reed-Solomon encoding

Functional Configuration



Block Diagram



Link Margin Summary

Link	Data Rate	Margin (db) Max range	Comment
Ka-Band Downlink	26 Mbps	+3.5 +>5 at GDS	0.7M HGA to 34M 10 deg at CAN
S-Band Downlink	8 kbps	+17.6	HGA to 34M
S-Band Uplink	2 kbps	+14.1	34M to HGA 200 watts
S-Band Uplink	1 kbps	+2.5	34M to OMNI 2 kw
S-Band Downlink	2 kbps	+3.7	OMNI to 34M
S-Band Return	1 kbps	+2.5	OMNI to TDRSS within the nominal TDRSS envelope
S-Band Forward	1 kbps	+0.6	TDRSS to OMNI within the nominal TDRSS envelope
Ranging		positive	Via DSN

TDRSS guarantees support with a margin of >0 dB

Component Summary

Component	DC Power (watts) pk/avg	Mass (kg)
S/Ka Transponder (2) *	30/26	6.2
S/Ka Antenna (0.5 Meter)	30/2	6
10 watt Ka TWTA (2)	30/22	7
5 watt S-band PA (2)	20/2	1
S-band omni (2)	--	2
Diplexer (2)	--	1.2
Triplexer	--	1
Hybrids (2)	--	0.4
Switches (4)	--	1
Isolator and cabling, misc	--	3
TOTALS	110/52	28.8

*This Transponder does not exist, but could be developed from the X/Ka SDST with NRE. Separate S-band transponders and Ka-band transmitters that exist could be used but with additional weight of ~7 kg. NRE costs would have to be compared with the cost of separate units

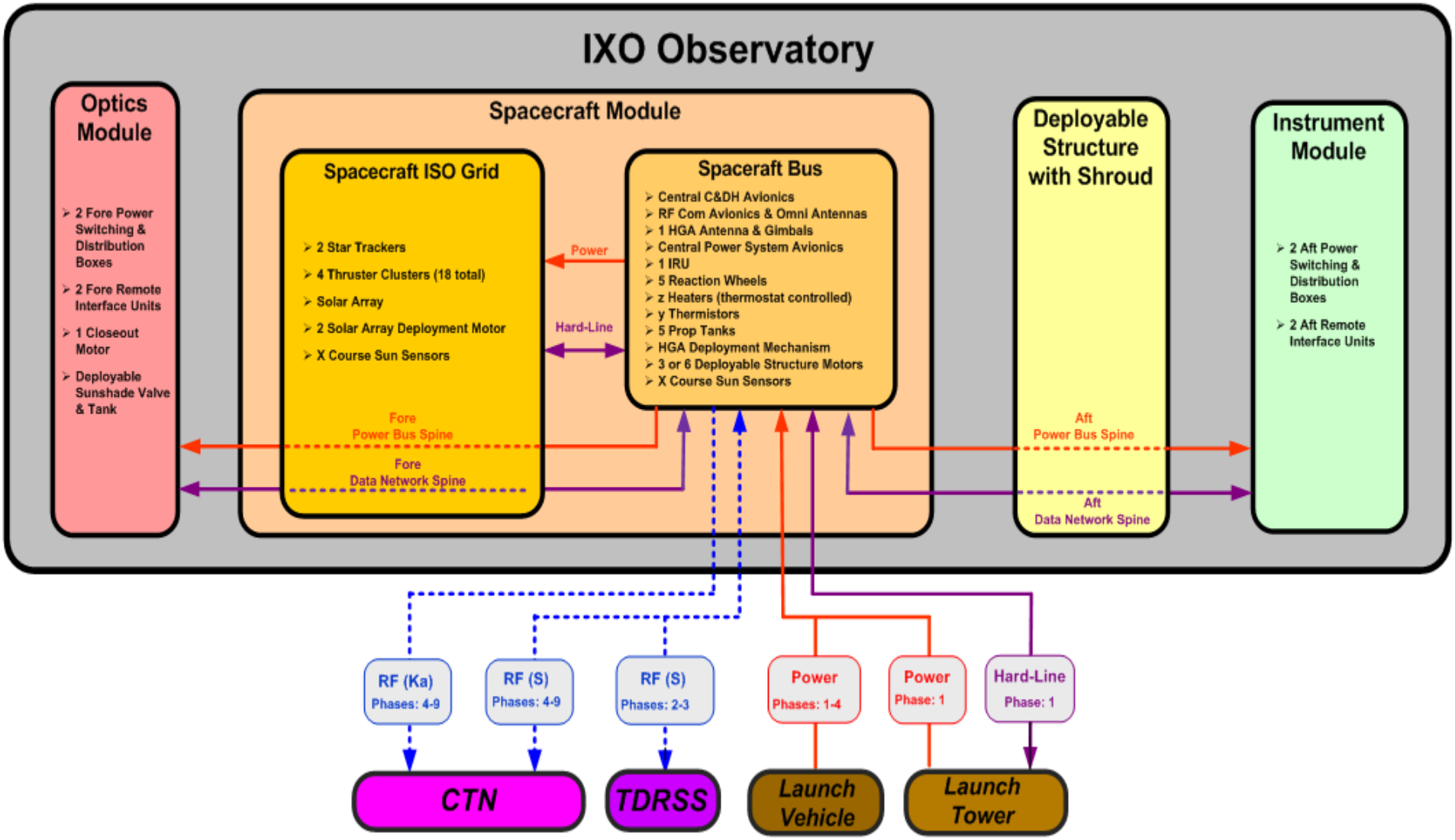
Avionics

IXO Avionics System Overview

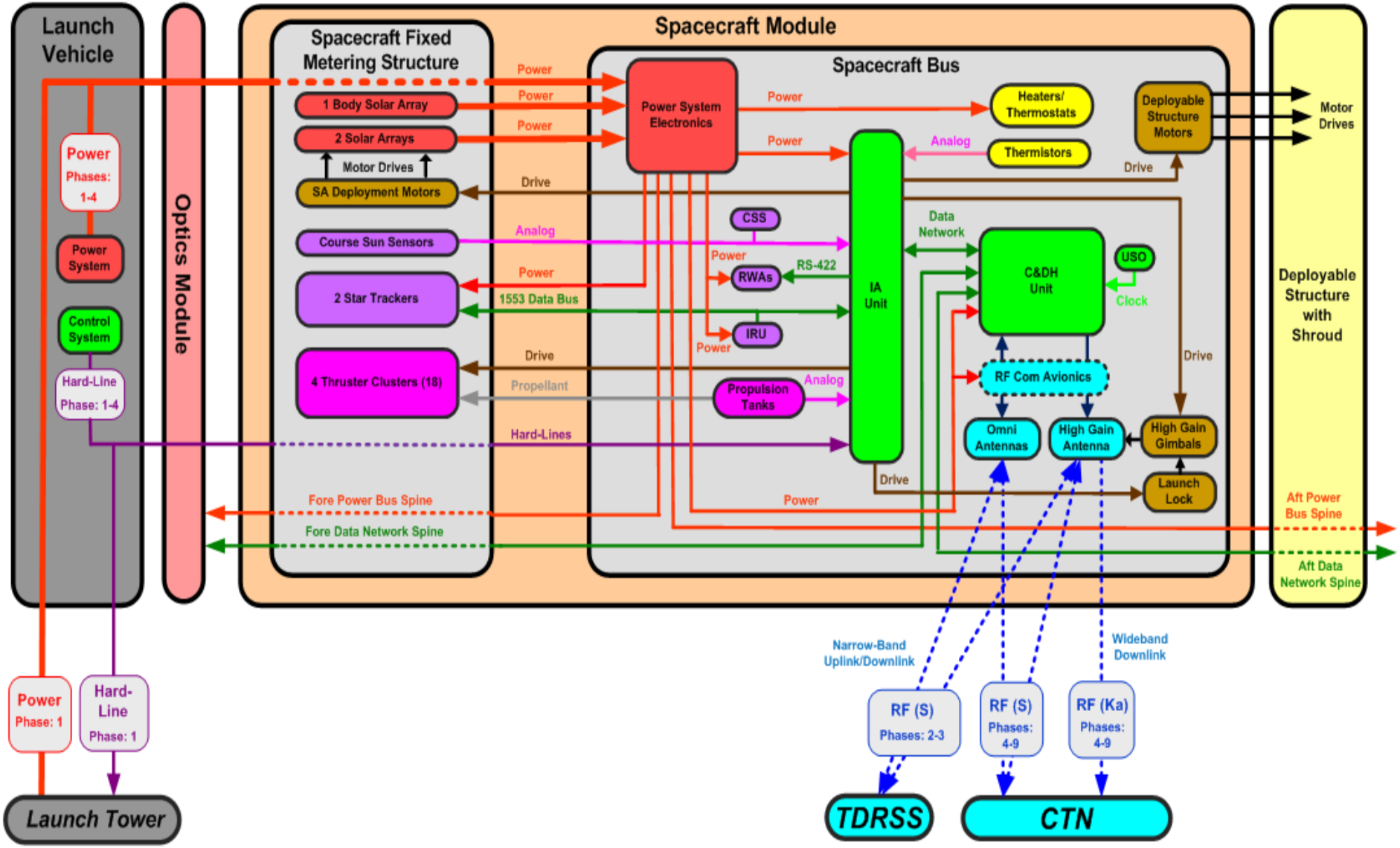
- **The IXO Avionics System utilizes a distributed architecture with minimal interfaces between the Spacecraft Module and the two end modules: Optics Module & Instrument Module. This architectural approach minimizes wiring harness mass, which is the heaviest part of an avionics system. It also minimizes development and I&T costs due to its highly modular design and simple interfaces.**

	Sub-Systems	LRUs	Functions	LRU Sizes (cm) H x D x L	Mass (kg)	Power (W)
Optics Module	C&DH	RIU	▪ Power Switching/Distribution ▪ Master Control & Monitoring	24.5 x 25.0 x 17.2	19.6	12
Spacecraft Fixed Metering Structure						
Spacecraft Bus	C&DH	C&DH Unit	▪ Baseband Telecom ▪ Network Master	24.5 x 25.0 x 29.4	15.6	55
		IA Unit	▪ Spacecraft Computer ▪ Sensor/Effector Interface	24.5 x 25.0 x 23.3	25.6	35
		USO	▪ Observatory Clock	4.0 x 4.0 x 10.0	0.5	3
Deployable Structure						
Instrument Module	C&DH	RIU	▪ Power Switching/Distribution ▪ Master Control & Monitoring	24.5 x 25.0 x 20.2	18.1	17
Observatory Totals					**79.6**	**122**

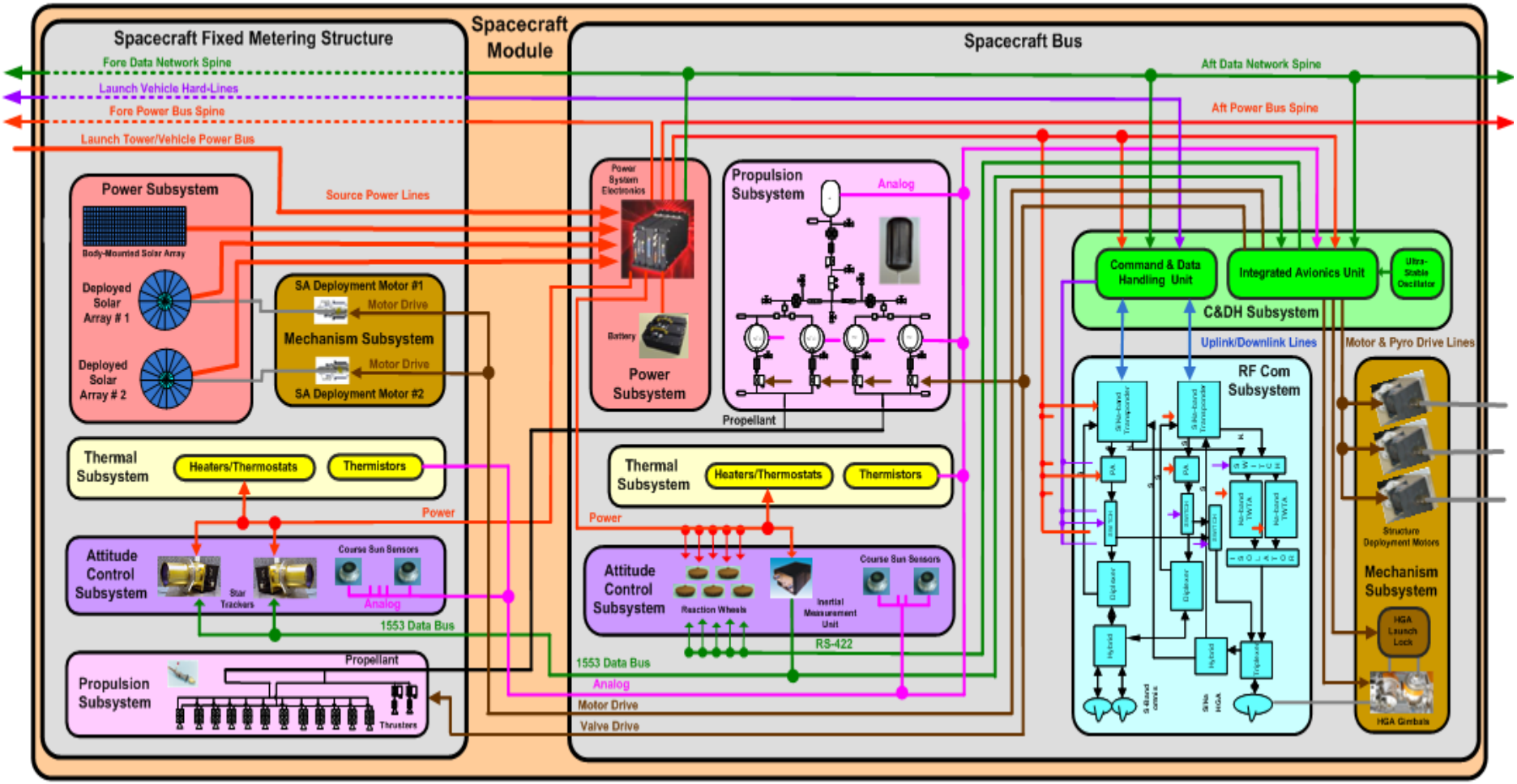
Level-2 Design: Module Functions



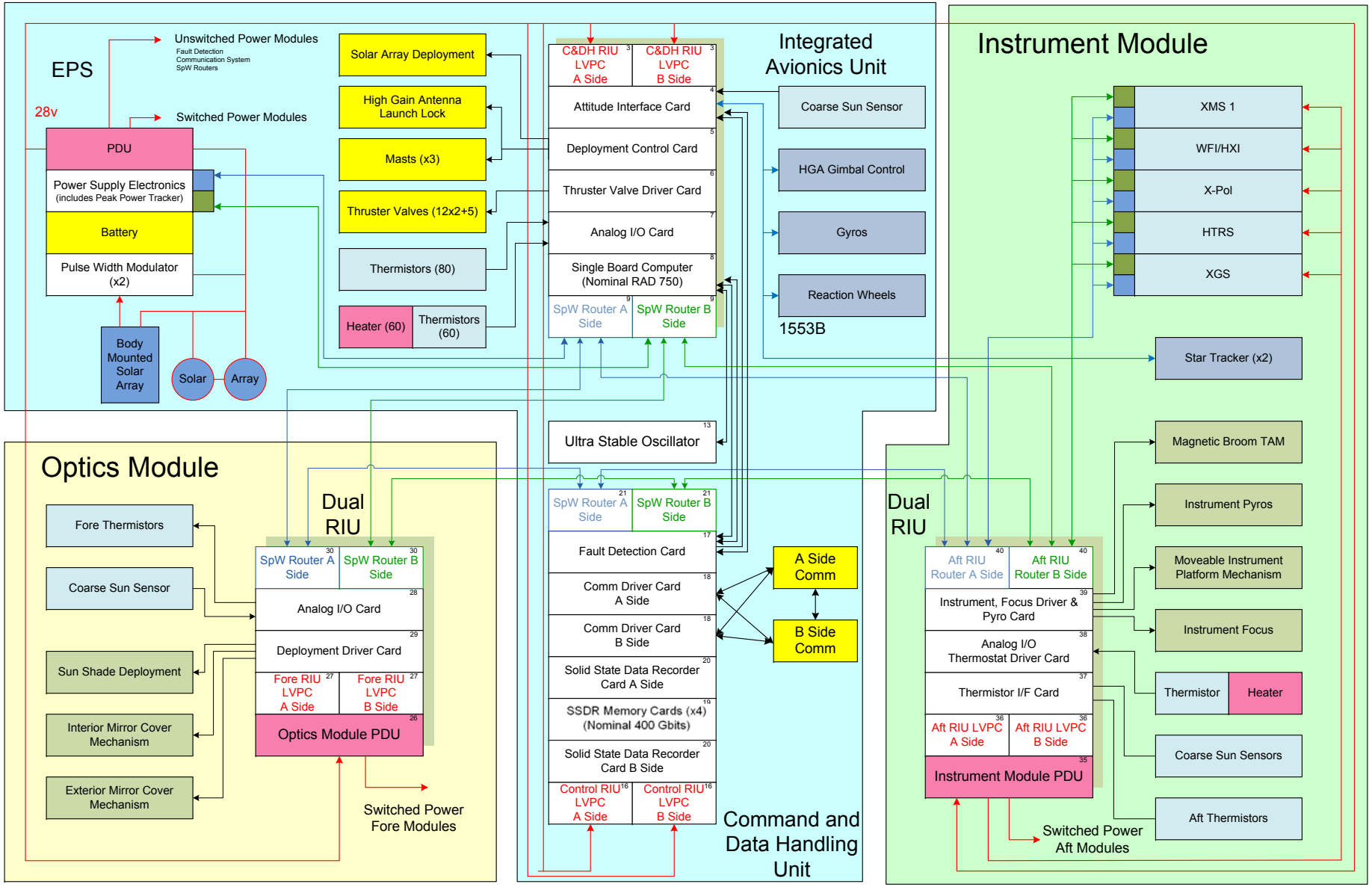
Level-3 Design: Avionic System Diagram



Level-3.5 Design: Spacecraft Module Diagram Showing Subsystems and Line Replaceable Units



Level-4 Design: Sub-Assemblies & Circuit Card Assemblies



Technologies and Building Blocks

- All technology used for the implementation of the avionics architecture are currently at TRL-6.
- The following key technologies were employed:
  - BAE RAD 750 Single Board Computer (6U).
  - 0.5 Gbit SDRAM Memory Parts.
  - Spacewire Data Network Interface, VHDL, and LVDS.

IXO Avionics Mass Power and Size Summary

Unit	Mass(kg)
Integrated Avionics Unit	25.77
Ultra Stable Oscillator	0.5
Command and Data Handling Unit	15.56
Optics Module RIU	19.62
Instrument Module RIU	18.11
Total	79.56

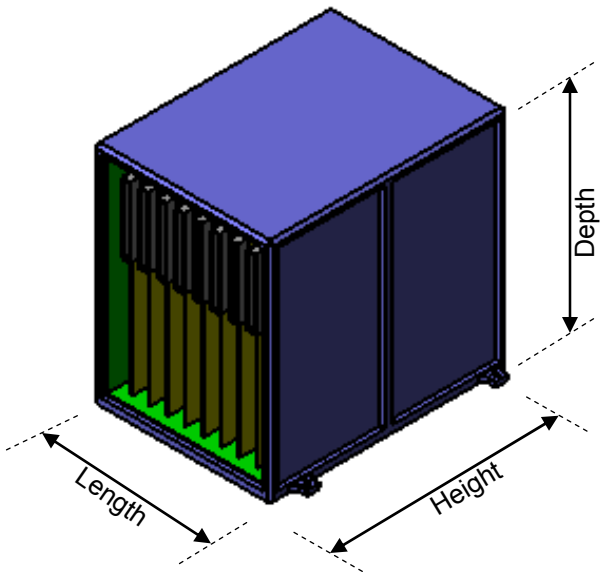
Unit	Mass(kg)
Integrated Avionics Unit	35.0
Ultra Stable Oscillator	3.0
Command and Data Handling Unit	55.0
Optics Module RIU	12.0
Instrument Module RIU	17.0
Total	122.0

Unit	H	D	L
Integrated Avionics Unit	245	250	233
Ultra Stable Oscillator	100	100	100
Command and Data Handling Unit	245	250	294
Optics Module RIU	245	250	172
Instrument Module RIU	245	250	202

Integrated Avionics Unit Mass and Size

Integrated Avionics Mass/Size Calculator

Number of C&DH Cards not including FD&R	6		
Fault Detection and Recovery	no		
Strings (1-single, 2-dual, …)	2		
Integrated RIU (yes/no)	no		
Number of RIU cards	0		
Form factor (3u/6u)	6u		
Card Heigth (160/220)	220	mm	
Wall thickness	100	mills	
Partition Thickness	100	mills	
Card Slot Width (0.8in.=20.32mm or 1.2in.=30.48mm)	30.48	mm	
Height	245	mm	9.65
Depth	250	mm	9.84
Length Backplane	208	mm	8.18
Length Chassis	233	mm	9.17
Chassis Mass	3.57	kg	7.88
Card Mass	19.20	kg	42.34
Backplane	3.00	kg	6.62
Total Mass	25.77	kg	56.83 lbs.



V1.1.4

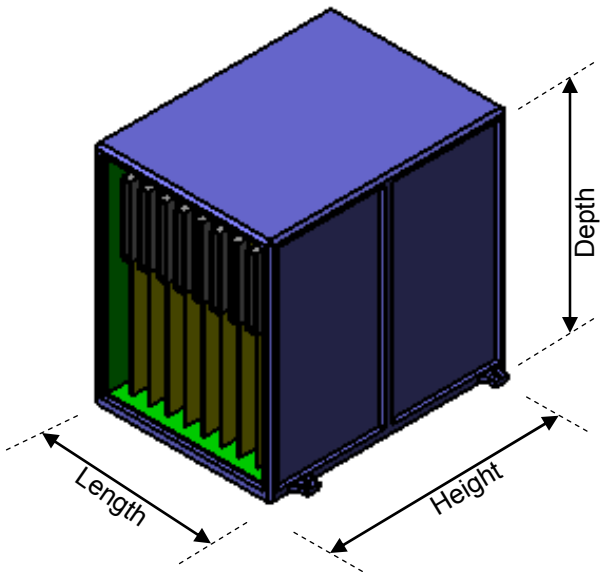
Integrated Avionics Unit Cards and Power Consumption

Component	Ident	Number	Launch	Science	Safe	Peak
Low Voltage Power Converter	3	1	7	9	9	24
Attitude Interface Card	4	2	0	7	7	7
Deployment Control Card	5	2	0	0	0	30
Thruster Valve Drive Card	6	4	0	0	0	30
Analog I/O Card	7	2	4	4	4	4
RAD 750 SBC	8	2	11	11	11	11
SpaceWire Router	9	1	4	4	4	4
Harness	10	1	0	0	0	0
Chassis	11	1	0	0	0	0
Total			26	35	35	110

Optics Module (Fore) RIU Mass and Size

Fore RIU Mass/Size Calculator

Number of C&DH Cards not including FD&R	7			
Fault Detection and Recovery	yes			
Strings (1-single, 2-dual, …)	2			
Integrated RIU (yes/no)	no			
Number of RIU cards	0			
Form factor (3u/6u)	6u			
Card Heigth (160/220)	220	mm		
Wall thickness	100	mills		
Partition Thickness	100	mills		
Card Slot Width (0.8in.=20.32mm or 1.2in.=30.48mm)	30.48	mm		
Height	245	mm	9.65	in.
Depth	250	mm	9.84	in.
Length Backplane	269	mm	10.58	in.
Length Chassis	294	mm	11.57	in.
Chassis Mass	4.29	kg	9.46	lbs
Card Mass	24.00	kg	52.92	lbs
Backplane	3.50	kg	7.72	lbs
Total Mass	31.79	kg	70.10	lbs



V1.1.4

Fore RIU comprise 4 Cards for FMA Thermal Control:

- Unregulated S/A power input
- 240 “stick-on” Heaters, individually controlled as 240 Heater Zones on the 60 FMA Modules
- 240 FETs
- 240 Thermistors

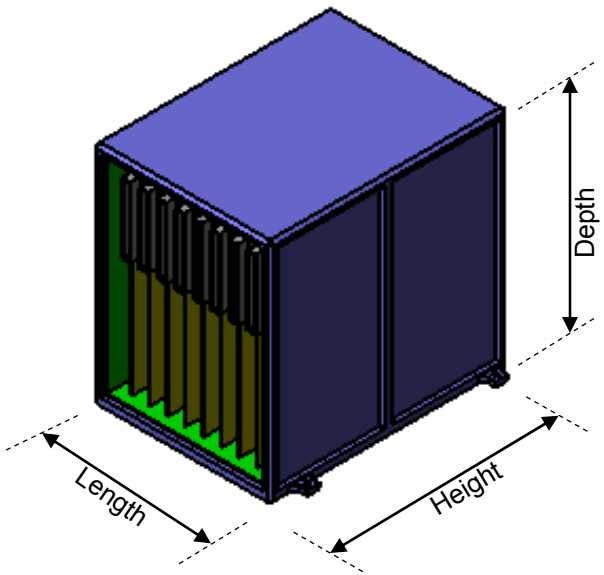
Optics Module (Fore) Cards and Power Consumption

Component	Ident	Number	Launch	Science	Safe	Peak
Optic Module PDU	26	1	0	0	0	1
Low Voltage Power Converter	27	1	4	4	4	12
Analog I/O Card	28	2	4	4	4	4
Deployment Control Card	29	2	0	0	0	30
SpaceWire Router	30	1	4	4	4	4
Harness	31	1	0	0	0	0
Chassis	32	1	0	0	0	0
Total			12	12	12	50

Instrument Module (Aft) RIU Mass and Size

Aft RIU Mass/Size Calculator

Number of C&DH Cards not including FD&R	4		
Fault Detection and Recovery	yes		
Strings (1-single, 2-dual, …)	2		
Integrated RIU (yes/no)	no		
Number of RIU cards	0		
Form factor (3u/6u)	6u		
Card Heigth (160/220)	220	mm	
Wall thickness	100	mills	
Partition Thickness	100	mills	
Card Slot Width (0.8in.=20.32mm or 1.2in.=30.48mm)	30.48	mm	
Height	245	mm	9.65
Depth	250	mm	9.84
Length Backplane	177	mm	6.98
Length Chassis	202	mm	7.97
Chassis Mass	3.22	kg	7.09
Card Mass	14.40	kg	31.75
Backplane	2.00	kg	4.41 lbs.
Total Mass	19.62	kg	43.25 lbs.



V1.1.4

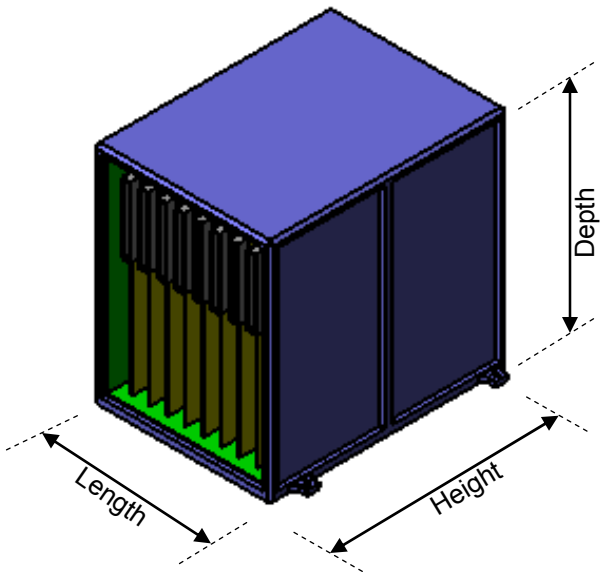
Instrument Module (Aft) Cards and Power Consumption

Component	Ident	Number	Launch	Science	Safe	Peak
Instrument Module PDU	35	1	0	0	0	1
Low Voltage Power Converter	36	1	5	5	5	5
Focus Driver	37	2	0	0	0	15
Analog I/O Card	38	2	4	4	4	4
Analog I/O Card	39	2	4	4	4	4
SpaceWire Router	40	1	4	4	4	4
Harness	41	1	0	0	0	0
Chassis	42	1	0	0	0	0
Total			17	17	17	32

Command and Data Handling Unit Mass and Size

C&DH Mass/Size Calculator

Number of C&DH Cards not including FD&R	8			
Fault Detection and Recovery	no			
Strings (1-single, 2-dual, …)	1			
Integrated RIU (yes/no)	no			
Number of RIU cards	0			
Form factor (3u/6u)	6u			
Card Heigth (160/220)	220	mm		
Wall thickness	100	mills		
Partition Thickness	100	mills		
Card Slot Width (0.8in.=20.32mm or 1.2in.=30.48mm)	30.48	mm		
Height	245	mm	9.65	in.
Depth	250	mm	9.84	in.
Length Backplane	269	mm	10.58	in.
Length Chassis	294	mm	11.57	in.
Chassis Mass	3.31	kg	7.30	lbs
Card Mass	12.80	kg	28.22	lbs
Backplane	2.00	kg	4.41	lbs
Total Mass	18.11	kg	39.93	lbs.



V1.1.4

Command and Data Handling Cards and Power Consumption

Component	Ident	Number	Launch	Science	Safe	Peak
Low Voltage Power Converter	16	1	12	12	12	12
Fault Detection and Recovery	17	1	3	3	3	3
Comm Driver Card	18	2	10	10	10	10
Memory	19	3	20	20	20	20
Solid State Data Recorder Card	20	2	6	6	6	6
Spacewire router	21	1	4	4	4	4
Harness	22	1	0	0	0	0
Chassis	23	1	0	0	0	0
Total			55	55	55	55

FSW

Requirements and Assumptions

- Payload support
  - Instrument packages are responsible for any data compression
  - Instrument packages are responsible for CCSDS packetization and time stamping of science data
  - C&DH/FSW provides commands/time distribution, accepts HK and science data
  - C&DH/FSW provides active thermal control for Flight Mirror Assembly (FMA)
  - C&DH/FSW provides command and control for instrument focus and rotating platform mechanism

- No Independent Attitude Control Electronics (ACE) CPU
  - Safehold control software will reside in the main processor
    - Processor-free survival safe mode implemented in the Attitude Interface Card
  - Spacecraft sun avoidance for mirror and detector decks

- No independent Power System Electronics (PSE) CPU
  - Management of the Main Power System will be part of the C&DH FSW
  - Battery charging control implemented as FPGA in the PSE

- Command & Data Handling including hardware command decryption. FSW to provide decryption key management
- High level of onboard autonomy
- Gimbaled High Gain Antenna, Fixed Solar Array
- No FSW end of mission requirements
- FSW development using ASIST for T&C GSE

FSW - C&DH Software Functionality

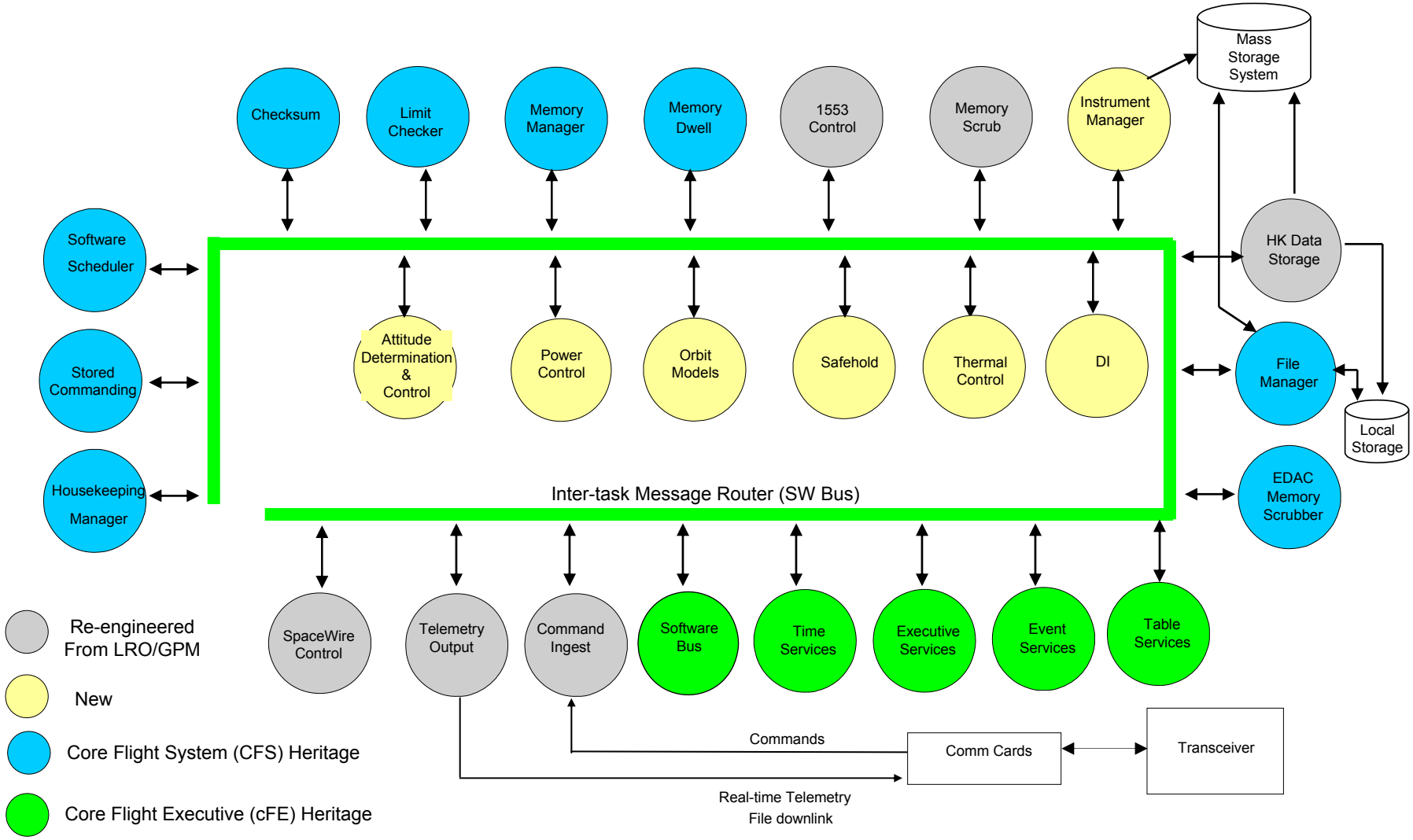
- Mission Specific Functions
  - Uplink/downlink management including command decryption key management
  - Failure Detection and Correction Management
  - Deployables Management
  - S/C Power Switched Services Management
  - Thermal control, payload Support
  - Time Management and Distribution

- Generic Features
  - Commercial real-time executive to provide multi-tasking, scheduling, intertask communication, interrupt and exception handling
  - Capability to perform hardware initialization
  - Bootstrap loader to provide basic DRAM and EEPROM memory loads and dumps capabilities
  - Provide in-flight capability to modify (patch) flight software
  - Command and data handling shall comply with the CCSDS definitions
  - Collection and distribution of on-board housekeeping data
  - S/C and payload commands distribution & management
  - Onboard autonomy
    - Absolute & relative time-tagged command sequences
    - Limit checker
  - Health & Safety Management
    - Memory Checksum Management
    - EDAC Memory Scrub Management
    - Parameter Table & Memory Management

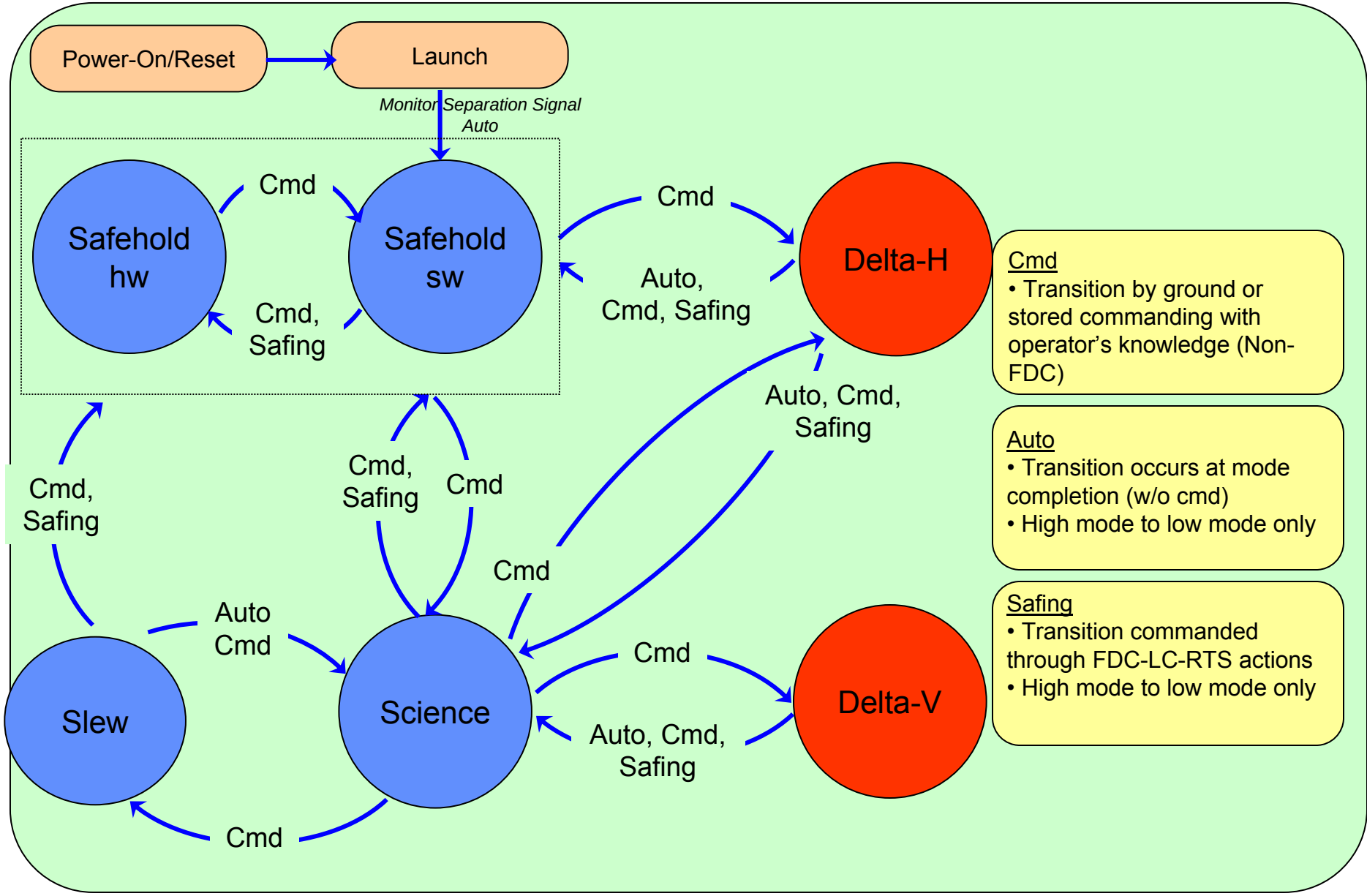
FSW - ACS Software Functionality

- Mission Specific Functions
  - Kalman Filtering
  - Process sensor and actuator data
    - Course Sun Sensors
    - Inertial Measurement Unit
    - Star Trackers
    - Reaction Wheels
    - Thrusters
  - Attitude determination
  - Manage and execute control modes
    - Cruise
    - Science
    - Safehold
    - Thruster
    - Slew
  - Manage system momentum
  - Sun avoidance for mirror and detector platforms
  - Generate sensor & actuator commands
    - Thrusters
    - Reaction Wheels
    - Star Trackers
    - High Gain Antenna Gimbals
    - Instrument Platform Mechanism
    - Instrument Focus
  - Detect and process ACS faults
- Generic (Heritage) Features
  - Math library functions
  - Onboard modeling
    - Solar Ephemeris
    - S/C Ephemeris

Flight SW Architecture



State Diagram

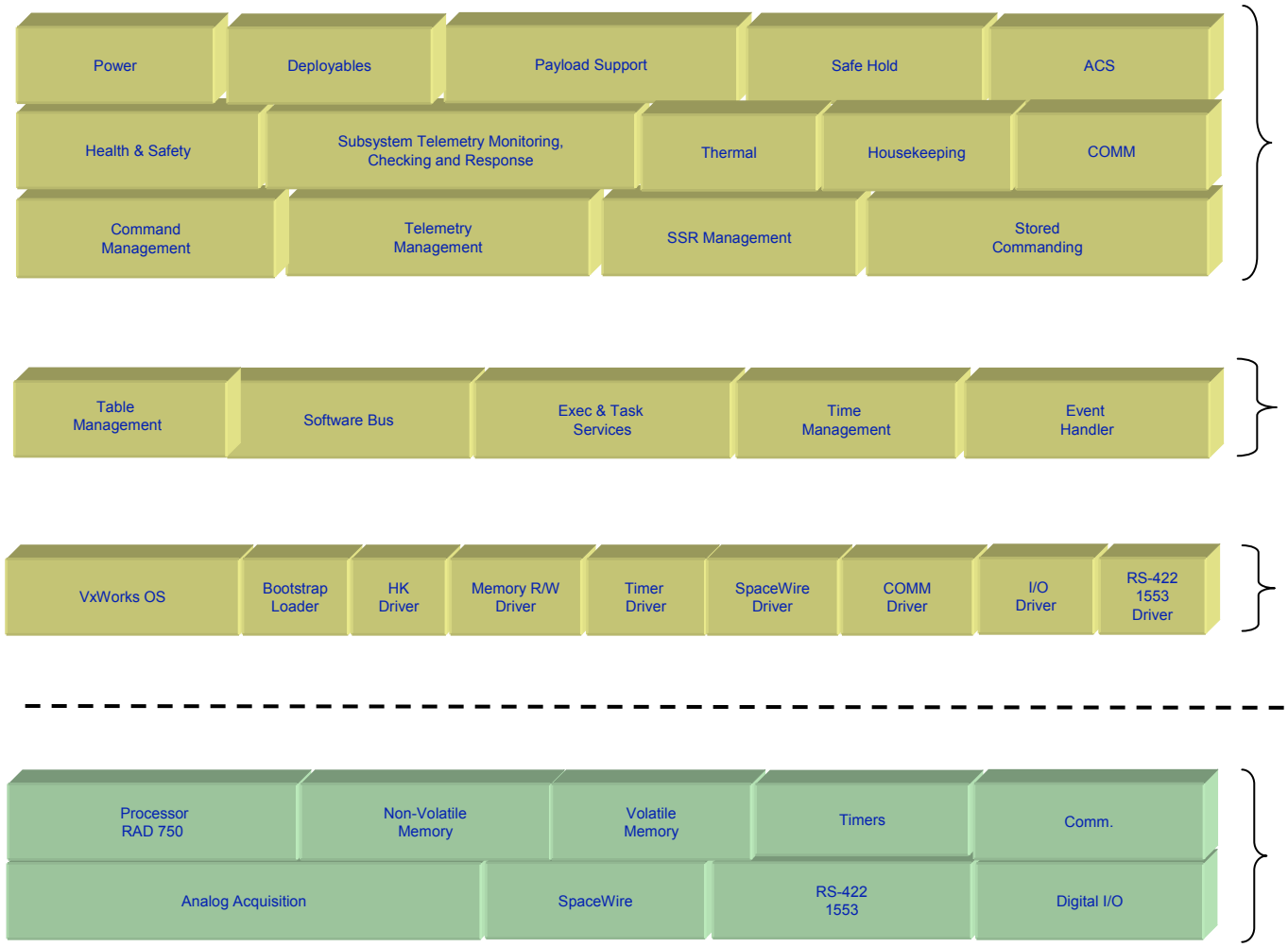


Cmd
• Transition by ground or stored commanding with operator's knowledge (Non-FDC)

Auto
• Transition occurs at mode completion (w/o cmd)
• High mode to low mode only

Safing
• Transition commanded through FDC-LC-RTS actions
• High mode to low mode only

Processor Layered Software Architecture & Associated Heritage



IXO
Application Layer
- Med/High Heritage For Common Functions (e.g., Stored Commanding, Health & Safety, Command Management),
- Low/No Heritage For Mission Unique Functions (e.g., Deployables, Payload, ACS, power)

System Support Layer
(582's Core Flight Exec)

OS Services Layer
(VxWorks OS,
582 OS Abstraction Layer)

IXO Physical
(Hardware) Layer

Processor Utilization Estimates

					Processor Adjusment		
	25	16	MHz Coldfire (effective rate)	BAE750(%)	12Mhz ST5/SD	115Mhz SDO	60Mhz LRO
	CPU Percentages			Base Value	0.75	7.19	3.75
Component	**50 Mhz**	**32 Mhz**	**Basis of Estimate**				
cFE	0.12	0.19	LRO B2.5 Measured	0.05			0.19
Housekeeping Data Acq	0.12	0.19	LRO B2.5 Measured	0.05			0.19
Health and Safety	0.24	0.38	Estimate	0.10			0.38
Memory Manager	0.01	0.02	LRO B2.5 Measured	0.01			0.02
Memory Dwell	0.17	0.26	LRO B2.5 Measured	0.07			0.26
Stored Commands	0.11	0.17	LRO B2.5 Measured	0.04			0.17
Limit Checker	0.10	0.15	LRO B2.5 Measured	0.04			0.15
Scheduler	1.46	2.29	LRO B2.5 Measured	0.61			2.29
1553 Bus Control	6.96	10.88	LRO B2.5 Measured	2.90			10.88
Command Ingest	0.01	0.02	LRO B2.5 Measured	0.01			0.02
R/T Telemetry Output	2.28	3.56	LRO B2.5 Measured	0.95			3.56
File Manager	0.02	0.04	LRO B2.5 Measured	0.01			0.04
Instrument Manager	16.80	26.25	Estimate	7.00			26.25
Data Storage	2.81	4.39	LRO B2.5 Measured	1.17			4.39
Memory Scrub	1.20	1.88	Estimate	0.50			1.88
Checksum	0.48	0.75	Estimate	0.20			0.75
Thermal Control	0.24	0.38	Estimate	0.10			0.38
Power Control	0.72	1.13	Estimate	0.30			1.13
Spacewire Bus Control	4.80	7.50	Estimate	2.00			7.50
Data Ingest	2.40	3.75	Estimate	1.00			3.75
HGA Control	2.40	3.75	Estimate	1.00			3.75
Attitude Control	96.00	150.00	Estimate	10.00			150.00
ACS Models	9.60	15.00	Estimate	1.00			15.00
Subtotal	**149.05**	**232.89**		**29.10**			

Estimated Resource Margins

For this chart, Margin = (Available – Estimate) / Available

Resource	Amount Available	Current Estimate	Current Margin	GOLD Rule Required Margin @Phase A
CPU (BAE750)	100%	29.10%	71%	50%
EEPROM(kB)	4096	1019	75%	50%
uP RAM(kB)	32768	6471	80%	50%

Code and Memory Estimates

Component	SLOC	EEPROM (KB)	SRAM (KB)		BOE
OS (VxWorks)		410.2	2034		LRO (compressed)
cFE		220.1	3061		LRO
Housekeeping	7214	14.0	40.8		LRO
Memory Manager	3660	6.5	29.8		LRO
Memory Dwell	1187	4.3	24.9		LRO
Stored Commands	8480	40.3	163.4		LRO
Limit Checker	15235	34.6	33.3		LRO
Scheduler	7649	20.7	29.2		LRO
1553 Bus Control	11910	21.9	86.6		LRO
Command Ingest	5306	7.8	31.7		LRO
Telemetry Output	11853	35.6	57.5		LRO
Data Storage	7338	11.5	54.9		LRO
Memory Scrub	7760	20.6	43		LRO
Checksum	7630	20.6	44		LRO
File Manager	7517	13.3	66.3		LRO
Instrument Manager	25000	35.0	350		Estimate
C&DH Library	11863	6.5	9		LRO
Power Control	2000	5.0	20		Estimate
Thermal Control	2000	5.0	20		Estimate
HGA Control	5000	8.0	30		Estimate
Models	6000	10.0	40		Estimate
Attitude Control	30000	40.0	150		Estimate
Data Ingest	2000	5.0	20		Estimate
Spacewire	1000	4.0	10		Estimate
Math Library	7721	4.7	7.8		LRO
GNC Shared Library	7261	6.0	1.6		LRO
Framework	8915	8.1	11.9		LRO
Total	**211499**	**1019.3**	**6471**		

Note: The VxWorks kernel and tasks are compressed in EEPROM. cFE and tables are uncompressed

FSW Development Approach

- Reuse LRO C&DH FSW (Med to high heritage, low risk - LRO scheduled to launch 2009)
  - LRO FSW Features (based on 582's Core Flight Executive)
    - Being developed using FSW best practices consistent w/NPR 7150.2
    - Onboard file systems and associated file transfer mechanisms
    - Onboard networks with standard interfaces
    - Standard application interfaces (API) for ease of development and rapid prototyping
    - Dynamic application loading, middleware (SB) provide dynamic cmd/tlm registration
    - POSIX APIs and open source Integrated Development Environment
  - Benefits
    - Will enable parallel collaborative development and system interoperability
    - Will automate many previously manual development activities
    - Will simplify technology infusion and system evolution during development and on-orbit
    - Will enable <u>rapid deployment of low cost, high quality mission software</u>

- New development for all mission specific components
  - ACS, Instrument support, mission-specific ops concept support, power electronics, etc.

Management Approach

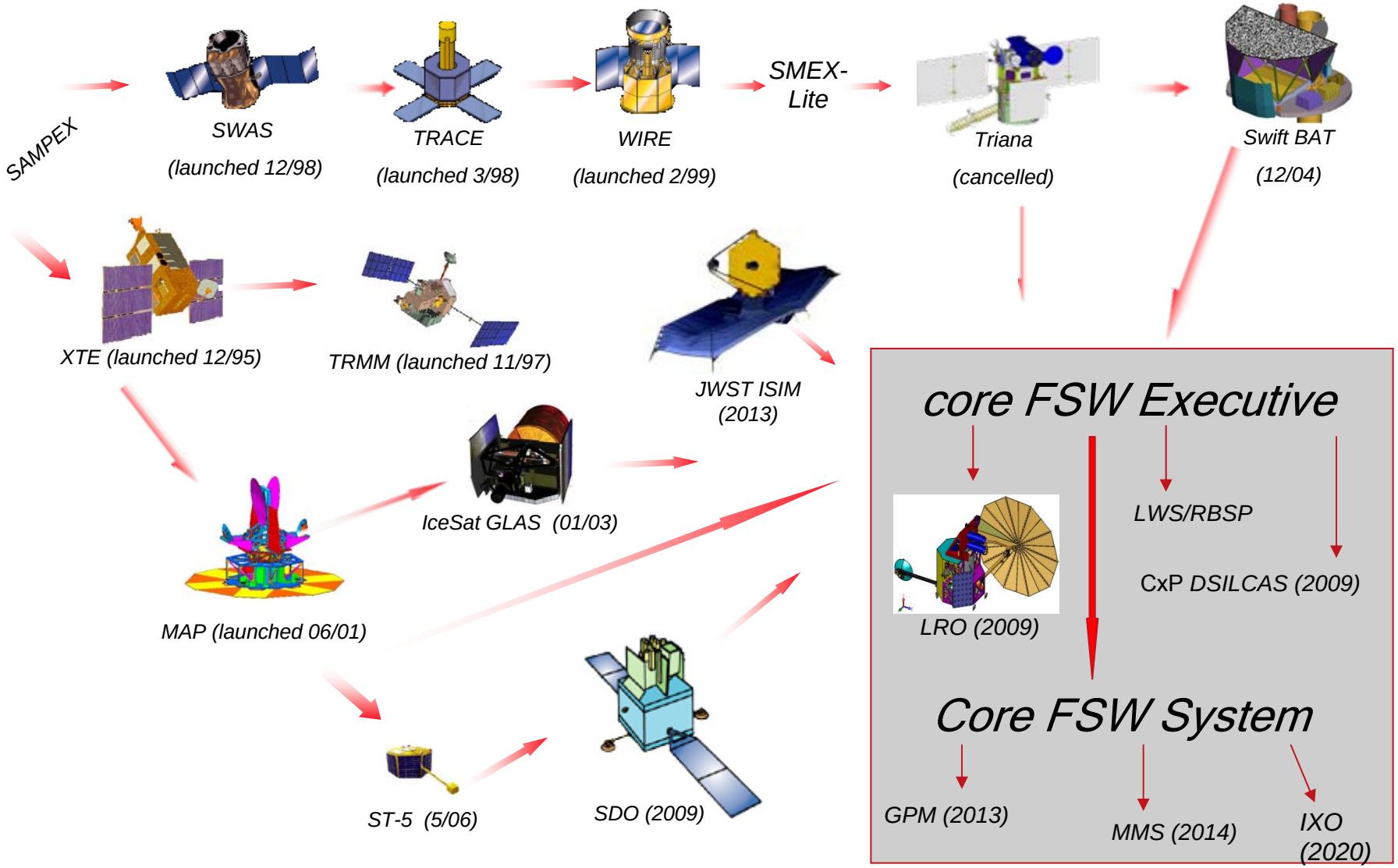
- Product Development Process Will Comply with GOLD rules and NPR 7150.2 (NASA Software Engineering Requirements)

- Development
  - Product Development Plan per 582 branch standards, approve by Branch & Project
  - Detailed FSW development schedule integrated with project & subsystems schedules
  - Requirements management using MKS tool
  - Monthly PSR with AETD & project; branch status reviews
  - Weekly system engineering meetings, FSW team meetings
  - FSW Design & Code reviews
  - Major milestones (SCR, PDR, CDR, etc.)

- Configuration Management
  - FSW CM Plan per 582 branch standards, approve by Branch & Project
  - Commercial CM tool (i.e., MKS) to manage source codes and document
  - Proposed FSW changes affecting missions requirements, cost and/or schedule will be forwarded to Project level CCB

- Test Plan
  - FSW Test Plan per 582 branch standards, approve by Branch & Project

GSFC Flight Software Architecture Heritage



Environments

Radiation

Micrometeorite

Solar Cycle Effects

- Solar Maximum
  - Trapped Proton Levels Lower
  - GCR Levels Lower
  - Solar Events More Frequent & Greater Intensity
- Solar Minimum
  - Trapped Protons Higher
  - GCR Levels Higher
  - Solar Events Are Less Frequent & Have Lower Intensity

- Solar Min: Calendar years 2016 – 2019
- Solar Max: Calendar years 2020 – 2025
- Solar Min: Calendar years 2026 – 2029

Total Ionization Dose – 10-year Mission

Total mission dose (rad)

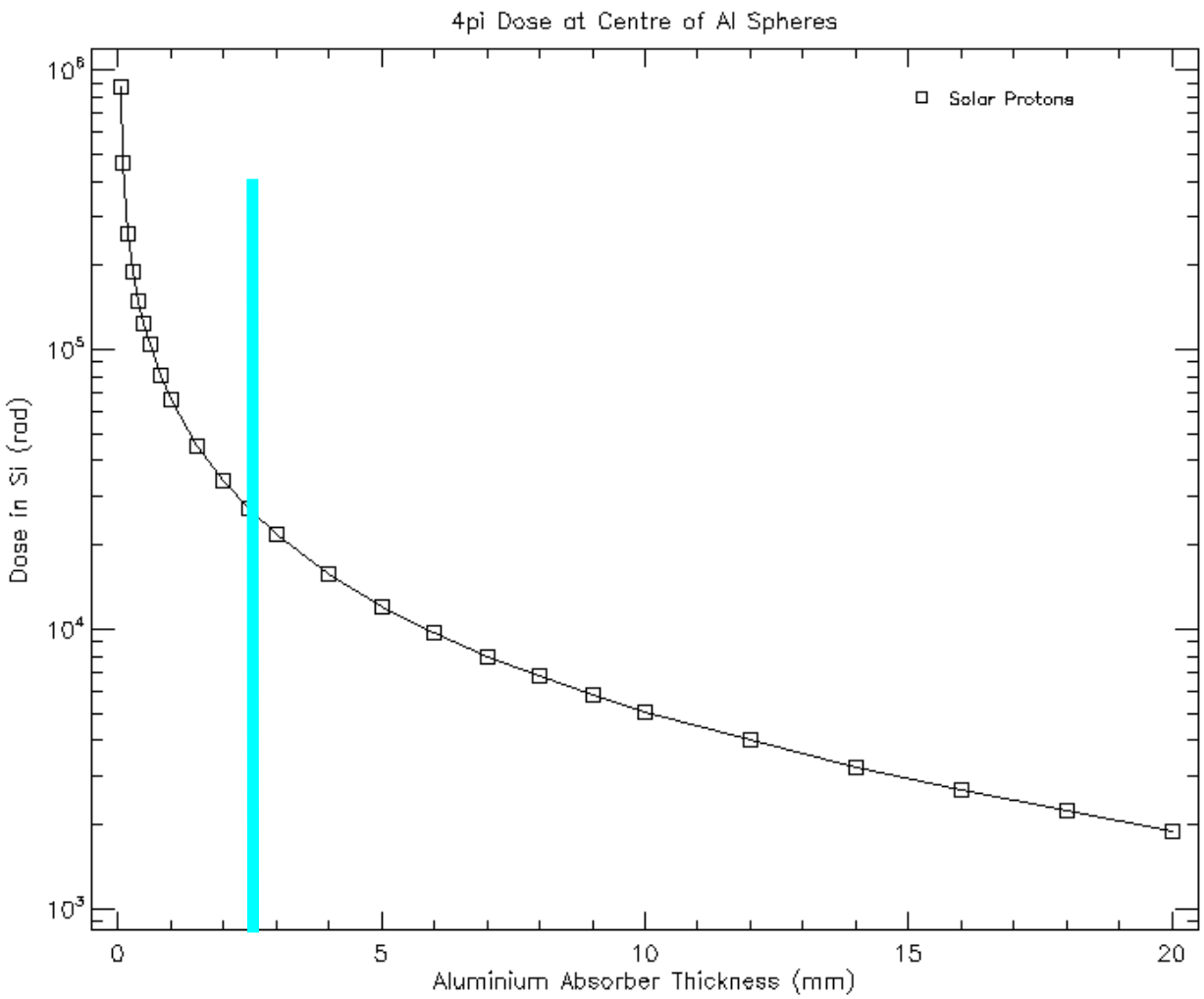
Al absorber thickness			Total *	Solar protons
(mm)	(mils)	(g cm^{-2})		
0.050	1.968	0.014	8.706E+05	8.706E+05
0.100	3.937	0.027	4.634E+05	4.634E+05
0.200	7.874	0.054	2.584E+05	2.584E+05
0.300	11.811	0.081	1.897E+05	1.897E+05
0.400	15.748	0.108	1.501E+05	1.501E+05
0.500	19.685	0.135	1.236E+05	1.236E+05
0.600	23.622	0.162	1.047E+05	1.047E+05
0.800	31.496	0.216	8.077E+04	8.077E+04
1.000	39.370	0.270	6.612E+04	6.612E+04
1.500	59.055	0.405	4.537E+04	4.537E+04
2.000	78.740	0.540	3.406E+04	3.406E+04
2.500	98.425	0.675	2.691E+04	2.691E+04
3.000	118.110	0.810	2.189E+04	2.189E+04
4.000	157.480	1.080	1.574E+04	1.574E+04
5.000	196.850	1.350	1.201E+04	1.201E+04
6.000	236.220	1.620	9.727E+03	9.727E+03
7.000	275.590	1.890	8.007E+03	8.007E+03
8.000	314.960	2.160	6.759E+03	6.759E+03
9.000	354.330	2.430	5.859E+03	5.859E+03
10.000	393.700	2.700	5.075E+03	5.075E+03
12.000	472.440	3.240	4.005E+03	4.005E+03
14.000	551.180	3.780	3.211E+03	3.211E+03
16.000	629.920	4.320	2.651E+03	2.651E+03
18.000	708.660	4.860	2.247E+03	2.247E+03
20.000	787.400	5.400	1.898E+03	1.898E+03

Values do not include 2x standard design margin

< Standard level for 100-mil Al equivalent shielding: 27 krad

* Dose on Si in rads

10-year Extended Mission Dose-Depth Curve



Values do not include 2x standard design margin

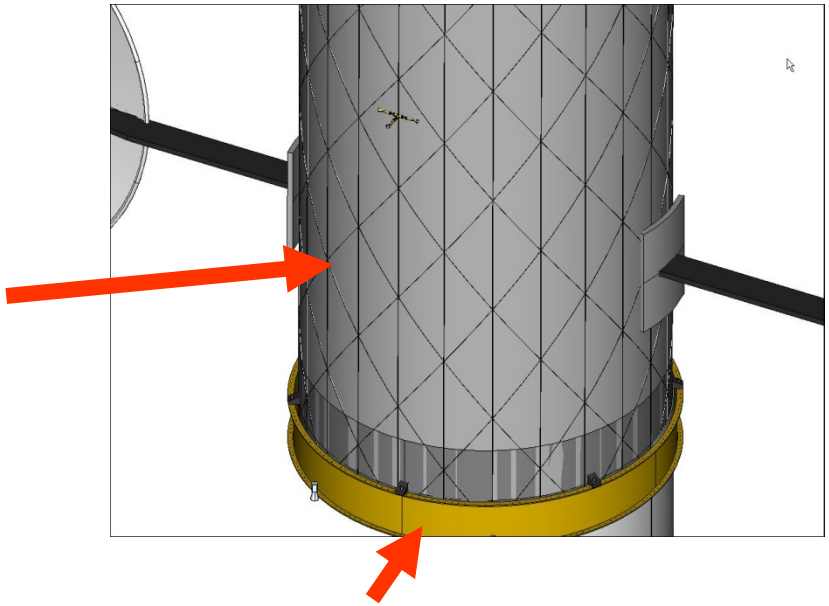
Under
100 mil Al
27 krad

Radiation Environment for 2020 Launch

- Earth-L2 TID ~ 100 rad @ 100 mil Al shielding. Insignificant in total TID.
- 5-yr design mission: 23 krad on Si @ 100 mil Al shielding. Design for 46 krad
- 10-yr extended mission: 27 krad on Si @ 100 mil Al shielding (due to solar min. conditions). Design for ~ 54 krad.

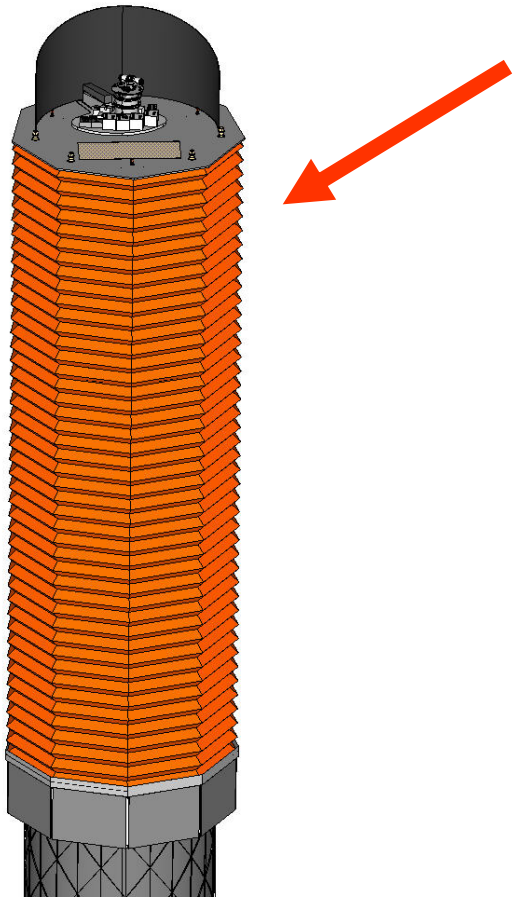
- Severe Environment for Single Events Effects
  - Devices fully exposed to Galactic Cosmic Rays and heavy solar particles
  - See background slides for a template SEE mitigation plan
  - Mitigation techniques are required for SEE vulnerable parts
    - Triple modular redundancy (TMR) works well for FPGAs
    - Error detection hardware is needed for masking out bit flips, resets, cycling power, etc.

Micrometeorite Threat - Fixed Metering Structure and FMA



- Fixed Metering Structure:
  - About 1-2 micrometeoroid penetrating impacts expected.
  - Estimated minimum impactor diameter is 0.091 cm.
  - Low probability of impactors of more than 0.3 cm diameter.
- Flight Mirror Assembly:
  - For the purpose of this study, failure is defined as penetration of the assembly. The geometry of the Flight Mirror Assembly (FMA), as well as the arrangements of the mirror foils, limits the probability of micrometeoroid penetration from this side of the observatory. The working assumption is that micrometeoroids striking the FMA are crushed when impacting multiple internal surfaces, while the separation from the FMA to the bus and the instrument module and the internal baffles allows for energy to dissipate, further reducing the threat of micrometeoroids coming from the FMA side.
  - More detailed studies should be conducted to assess the probability of damage to the FMA due to micrometeoroids.

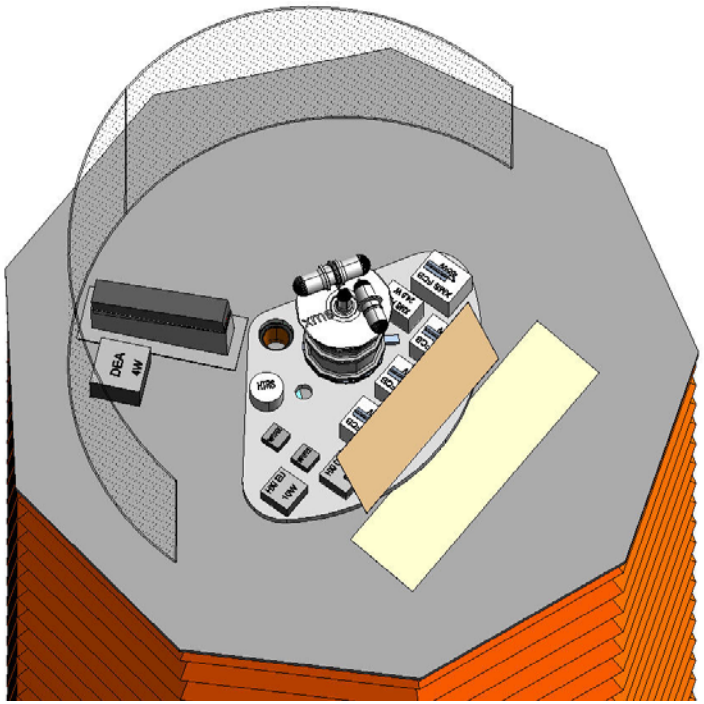
Micrometeorite Threat - Shroud



- Shroud:
  - Redesigned shroud, with two MLI blankets separated 10 cm (producing the effect of a Whipple shield), provides protection against micrometeoroids.
  - Low-level assessment for MLI blankets predicted a large number of penetrations, due to limitations of the available methods.
    - Hypervelocity Impact engineers have more advanced models, allowing less conservative and more accurate results.
      - » About 35 penetrations of the MLI shroud, with a minimum impactor diameter of 0.04 cm (information provided by Eric Christiansen, Hypervelocity Impacts expert at JSC).
  - Failure is defined as penetration of the innermost MLI layer.
  - Hole diameter not uniform; the outermost MLI layer is the smallest.

Micrometeorite Threat - Instrument Module

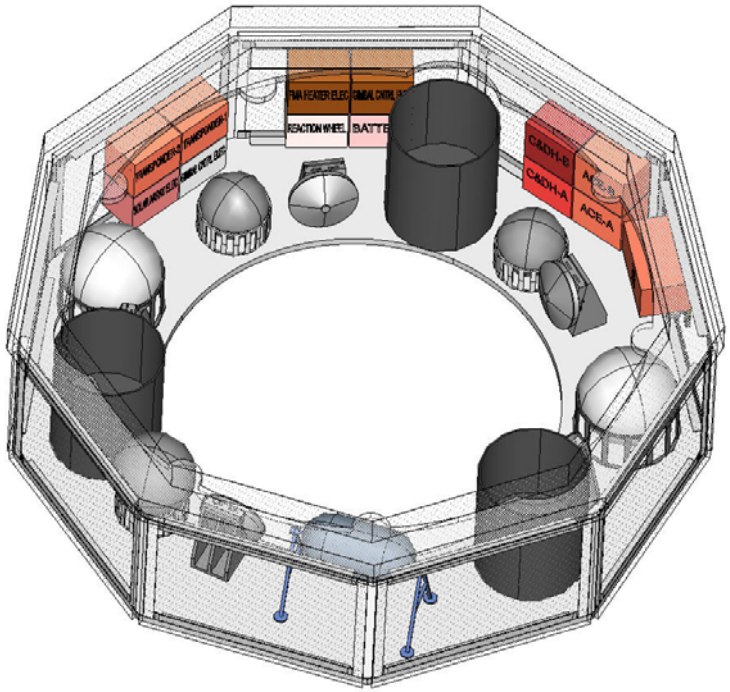
Failure is defined as penetration of the instrument or box housing. It is assumed that no particle crosses the FMA and reaches the Fixed Instrument Platform from the inside.



Instrument	Probability of penetration	Minimum particle diameter (cm)
XMS	0.13%	Ø 0.126
XGS CCD	1.80%	Ø 0.057
WFI/HXI	0.81%	Ø 0.057
HTRS	1.11%	Ø 0.057
XPOL	0.91%	Ø 0.057
Exposed Electronic Boxes	0.83%	Ø 0.057

Results are conservative.

Micrometeorite Threat - Central Bus Area



- **Hydrazine Tank:**
  - **Largest tank used as representative of all the tanks.**
  - **Low probability of damage (0.14%) by particles Ø 0.154 cm or larger.**
- **Electronic Boxes:**
  - **0.01% probability of penetration. This is representative of all the electronic boxes on that section.**

Results are conservative.

Micrometeorite Threat - Summary

- Current IXO design does not present any non-compliance with NASA regulations regarding limiting the generation of space debris.
- IXO was assessed for damage due to collision with micrometeoroids at L2. Although NASA-STD-8719.14 requires such analysis only for missions on Earth or Moon orbit, the assessment was performed to ensure that the micrometeoroid environment at L2 does not represent a threat to mission success.
  - The shroud is considered one of the most vulnerable components due to its large area and non-rigid composition (two MLI blankets with a middle gap, producing a Whipple-shield effect). However, only about 35 penetrations are predicted. The critical (minimum) diameter of the penetrating particle is 0.04 cm.
  - Since the shroud is not a solid panel, but two layered MLI blankets, a small penetration may be covered by the damaged Kapton layers, reducing or eliminating stray light.
- As a first approximation, the micrometeoroid protection for the payload, structures, electronic boxes and tanks is satisfactory.
  - Results are preliminary. More detailed analyses must be performed.