IXO Science Team Meeting
September 17-19, 2008
Garching/MPE

IXO Project Update
Mission Design Lab Summary

Jay Bookbinder

Outline

- Mission Design Parameters
- Payload complement
- Observatory Configuration
- Mission Configuration
- Issues and Summary

IXO Mission Design Lab Study

- Configuration Definition
  - Investigated mission options for deployable metering structure
  - Defined strawman parameters and payload
  - Developed error budget and plans for 5 arcsec angular resolution
- Study Focus:
  - 20 m focal length
  - 3.3 m diameter flight mirror assembly (slumped glass mirror technology)
  - Instrument complement consisting of Microcalorimeter/NFI, Wide Field Imager (WFI)/Hard X-ray Imager (HXI), X-ray Grating Spectrometer
  - Atlas V 551 launch vehicle
- Mission concept appears viable with positive margins
  - Provides "proof-of-concept" for extensible bench mission configuration

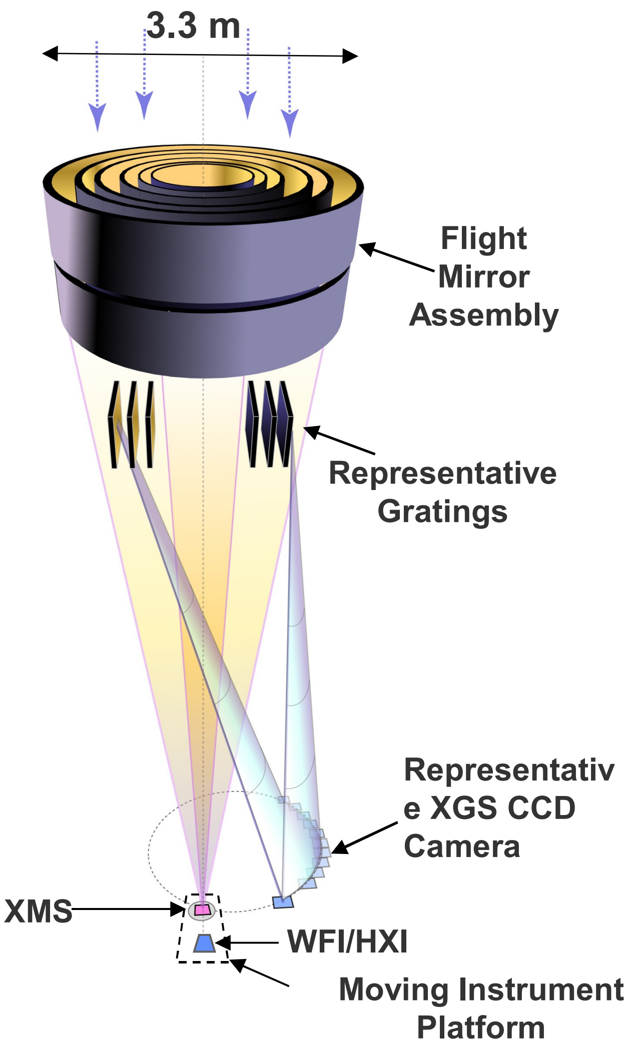
Strawman Payload Summary

Single Flight Mirror Assembly (FMA)

- 20 m focal length

Four instruments

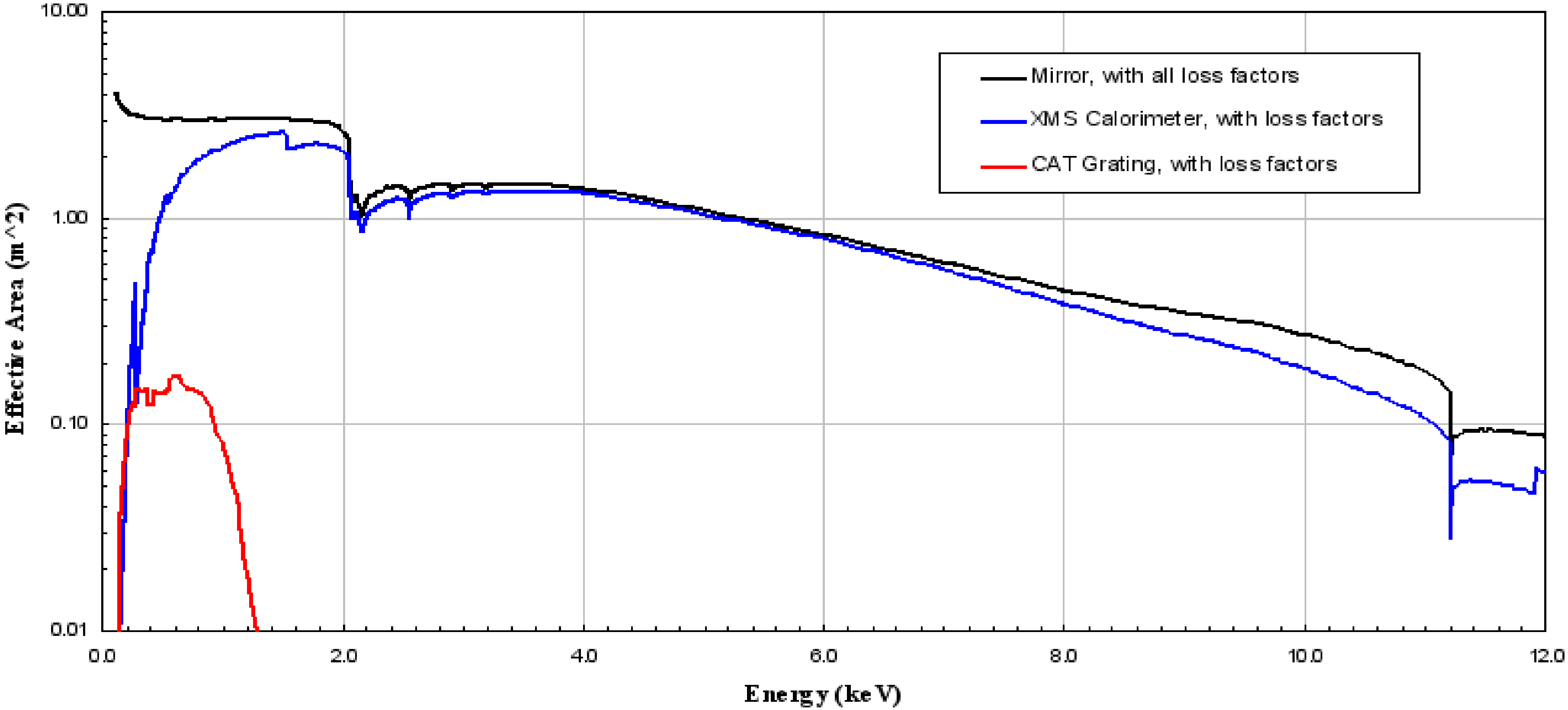
- X-ray Microcalorimeter Spectrometer (XMS)
  - Covers 0.6 to 10 keV
- Wide Field Imager (WFI)
  - Covers 0.1 to 15 keV with large FOV
- Hard X-ray Image (HXI)*extends the WFI bandpass to 40 keV
  - Assumed detector head within WFI envelope
- X-ray Grating Spectrometer (XGS)
  - Dispersive from 0.3 to 1 keV
  - Two grating arrays mount to aft of FMA
  - CCD camera for readout on fixed instrument platform



Note:

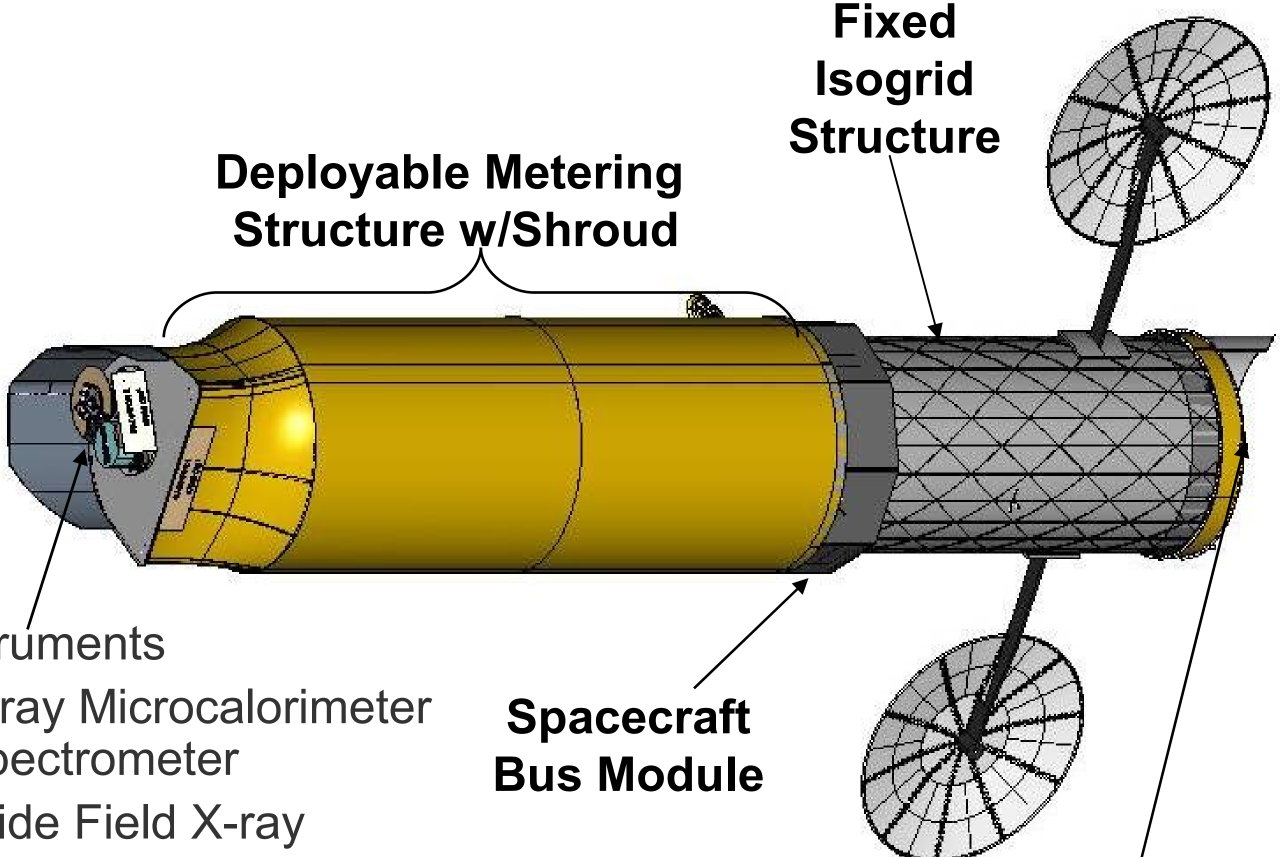
* Response by the FMA for this particular design does not meet desired level for high energies.

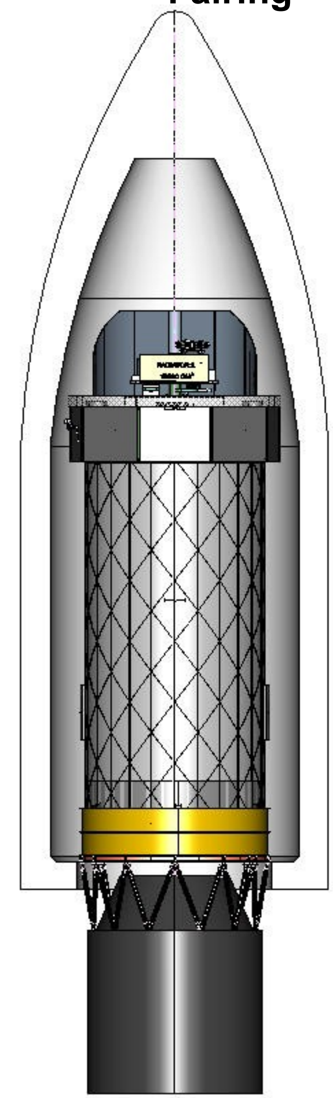
Mission Effective Area



- Flight Mirror Assembly
  - 3.3 m overall outer diameter (3.2 m largest diameter on optical surface)
  - 20 m focal length

IXO Single Mirror Configuration

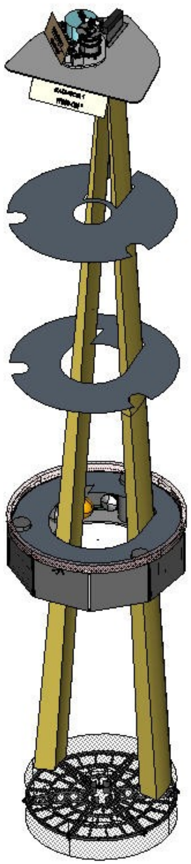


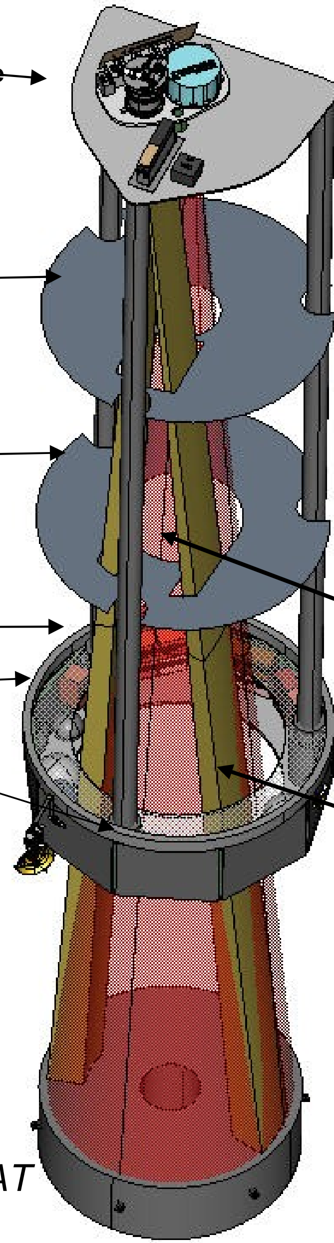


Instruments
- X-ray Microcalorimeter Spectrometer
- Wide Field X-ray Imager
- Hard X-ray Imager
- X-ray Grating Spectrometer

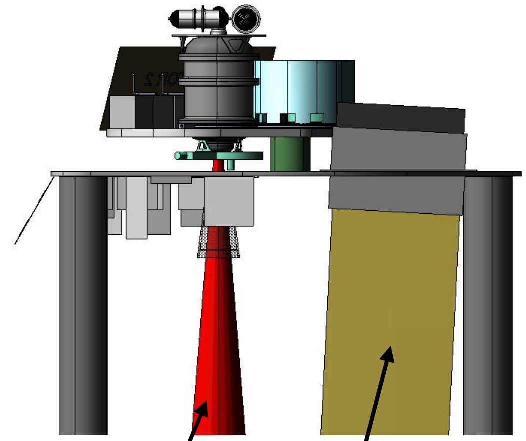
IXO Observatory – Optical Rays

Dispersed X-ray beam from XGS





FMA X-rays + CAT



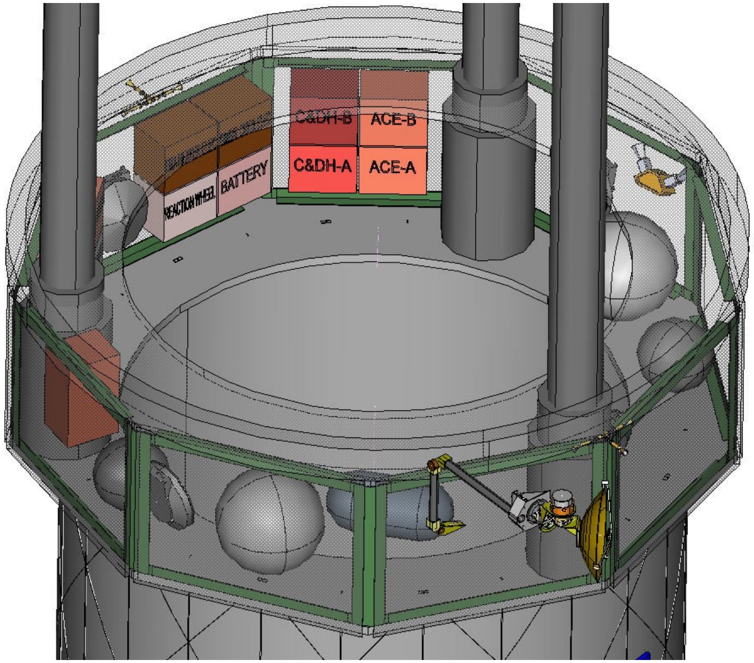
Focused X-ray beam from FMA

Dispersed X-ray beam from XGS

Spacecraft Bus

- Components mounted on Spacecraft Bus Top, Side, and Bottom Decks
  - Side panels hinged, open as “doors”

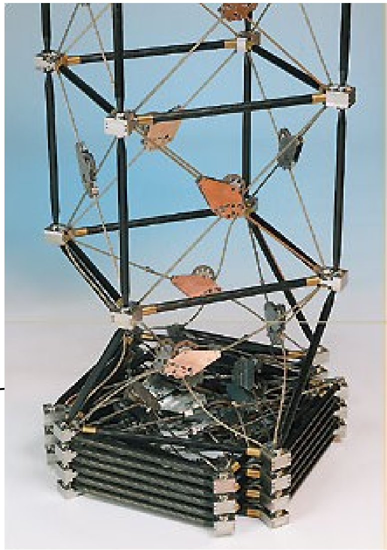
- Spacecraft Bus houses most of the Spacecraft Subsystem components
  - Attitude Control
    - 5 reaction wheels in biased arrangement
  - Propulsion
    - 5 tanks total
    - 12 5-n thrusters
  - Thermal
    - Traditional thermal control (heat-pipes, louvered
  - Electrical Power
    - 50 Ah LiIon battery

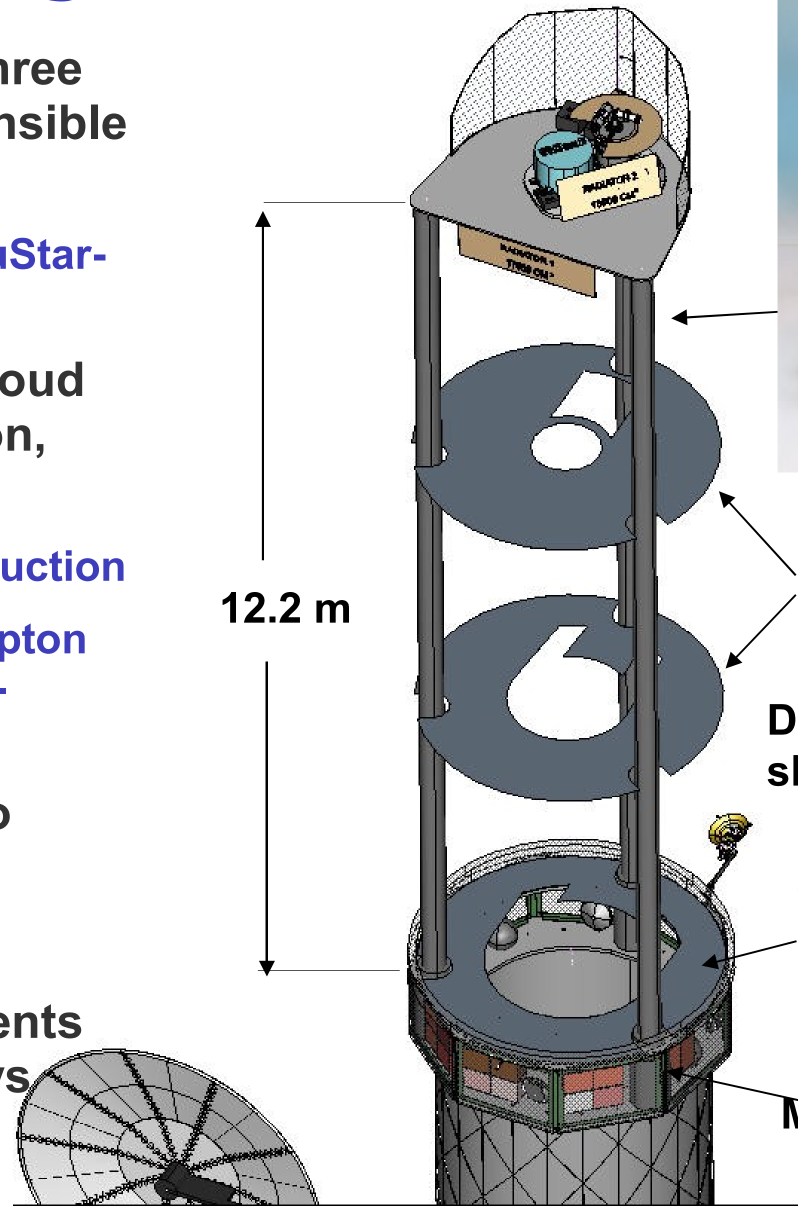


  - Command and Data Handling
    - Ka-Band for science (gimbaled 0.7 m HGA)
    - one 30 minute contact /day 26Mbps
    - S-Band omni
    - 300 Gb storage

Deployable Metering Structure

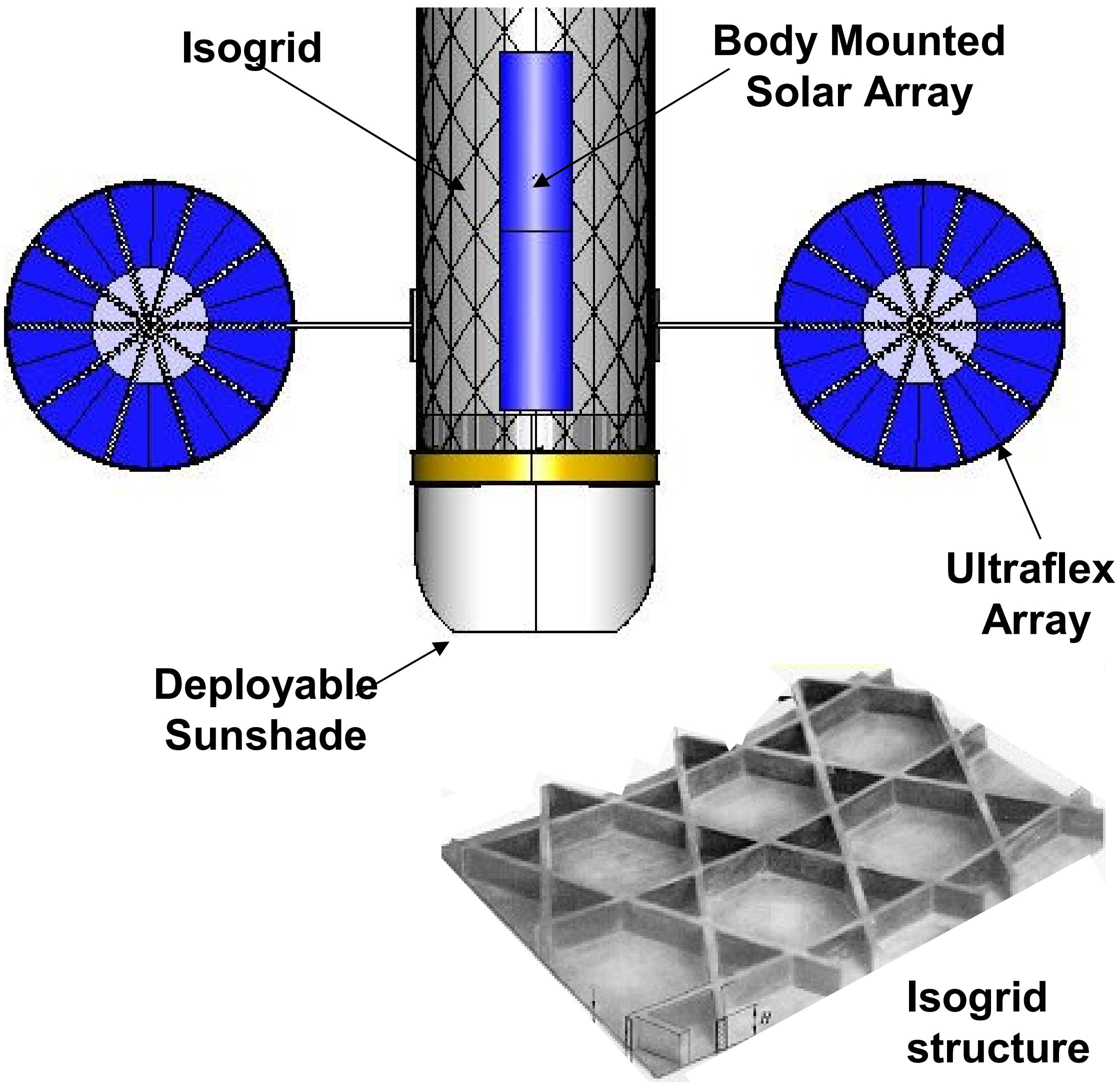
- Concept studied utilizes three deployable masts for extensible structure
  - Feasibility verified with NuStar-like mast
- Deployable Telescope Shroud provides thermal protection, light-tight environment
  - Pleated shade type construction
  - Multilayer blanket with Kapton outer skin provides micro-meteroid protection
- Two X-ray baffles attach to Shroud
  - Mylar with tantalum foil
- Harness between instruments and spacecraft bus deploys within mast system



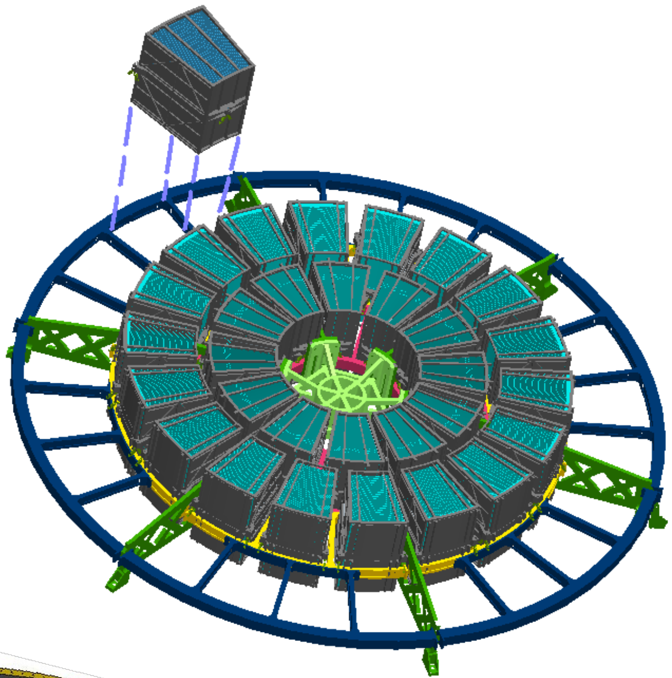


Fixed Metering Structure and Optics Module

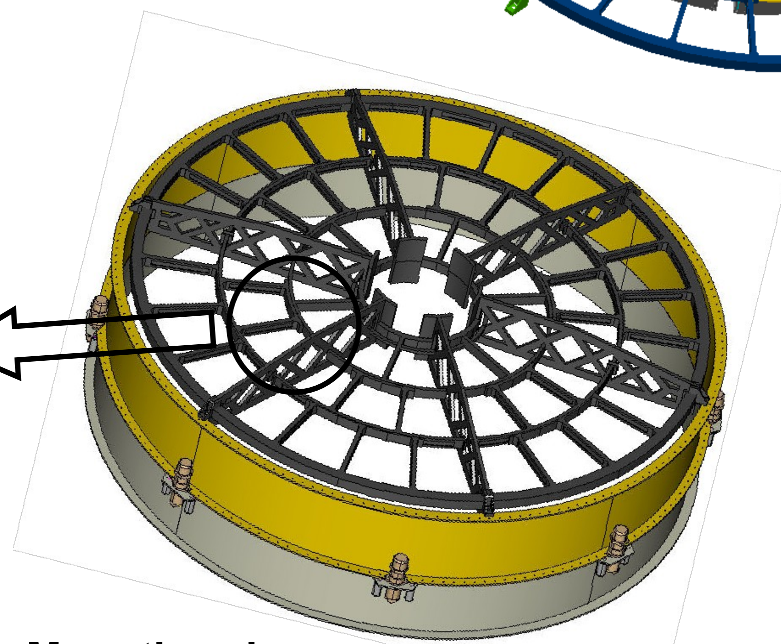
- Advanced Grid Stiffened composite (a.k.a. "isogrid") structure provides stiff lightweight primary structure
  - Same technology as Boeing 787 Dreamliner Sized for >10 Hz in launch configuration
- UltraFlex solar array positioned to minimize Center of Pressure to Center of Mass (CP-CM) offset
- FMA outer and inner covers w/ one time removal after Observatory outgassing

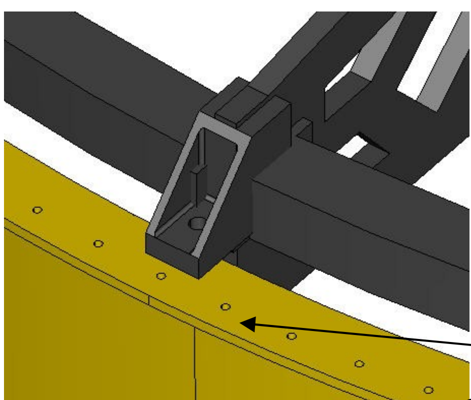


FMA to Spacecraft Interface



- FMA interfaces to the top flange of the Spacecraft Adapter Ring in 6-24 points. Six point FMA design shown here.
- FMA bolts through the flange of the spacecraft adapter at a bolt circle diameter of ~3448mm.
- Assume flange is flat within .030”.

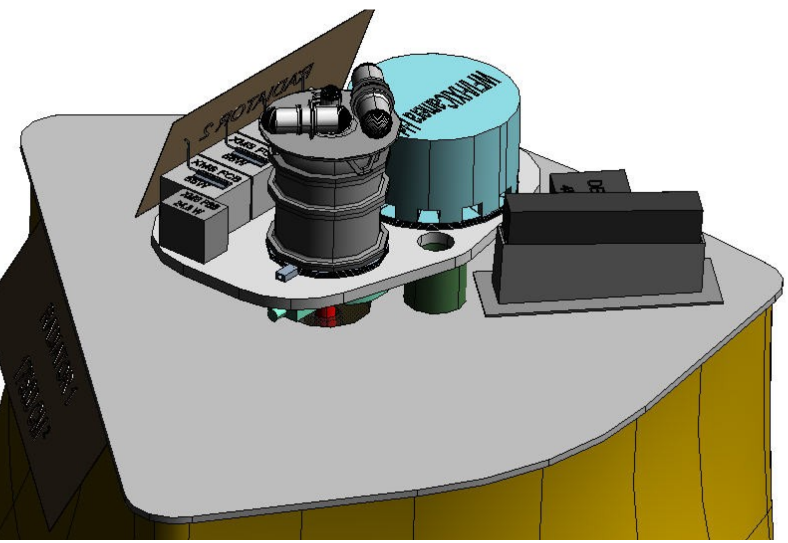


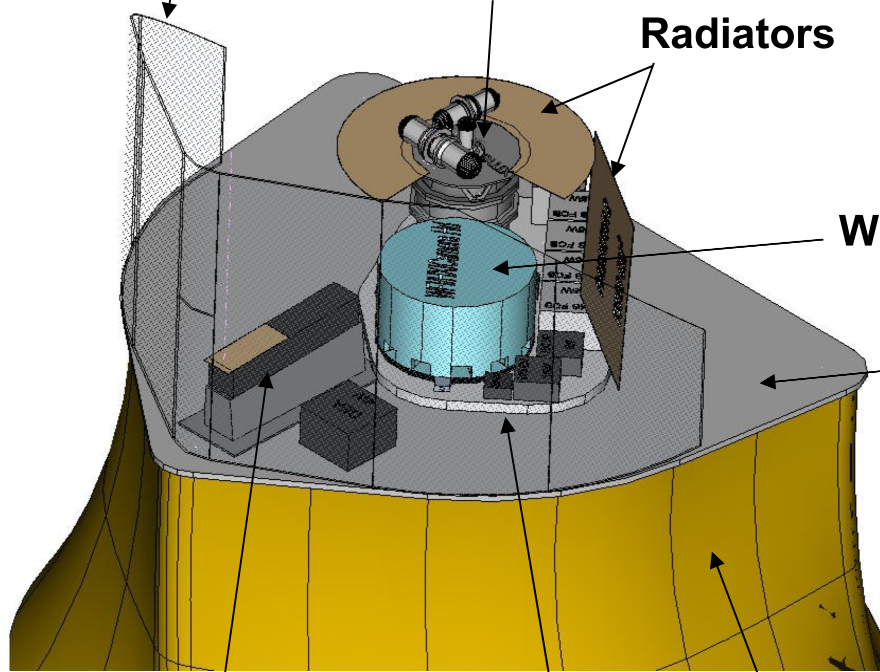


S/C Adapter Mounting ring

IXO Instrument Module

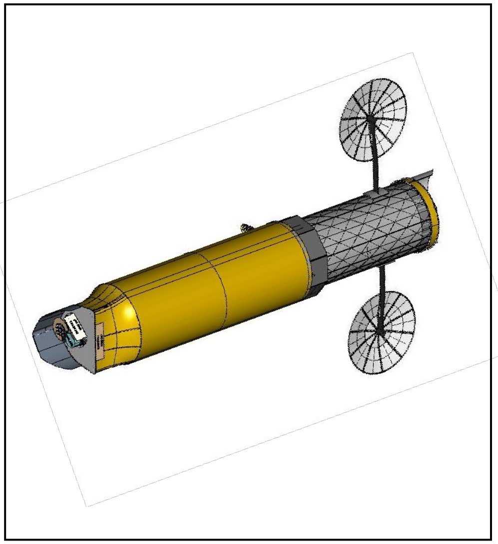
- XMS and WFI/HXI with pre-amp electronics mount on Moveable Instrument Platform
  - Focus adjust mechanisms on each instrument for initial adjustment on-orbit
- XGS CCD mounts to Fixed Instrument Platform (FIP)
  - Support structure provides proper interface to Rowland circle and baffle

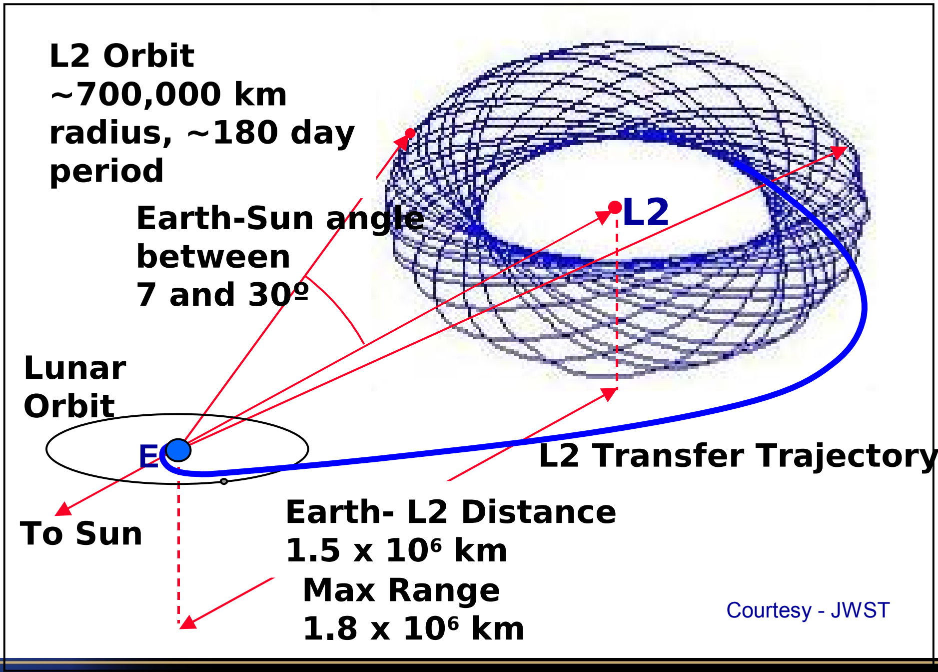




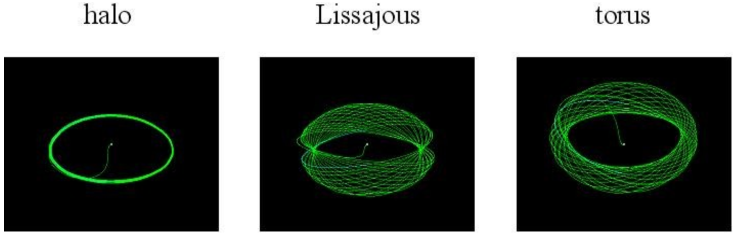
Mission Overview – Atlas LV

- Mission Life and Sizing
  - Class B Mission, no performance degradation w/ single point failure
  - Mission Life: 5 years required, 10 years goal, consumables sized for 10 years
- Launch
  - Launch on an Atlas V 551 medium fairing from KSC on 12/2020
  - Throw mass ~6342 kg (w/o Payload Attachment Fixture)
  - Direct launch into an L2 800,000 km semi-major axis "zero Insertion delta-v" halo orbit
  - 100 day cruise to L2
- Mission Orbit
  - At insertion, perform a maneuver to lower the Y amplitude to 700,000 km
  - Total Ionizing Dose (10 yrs): 27 kRad; severe Environment for Single Events Effects; micrometeoroid protection required

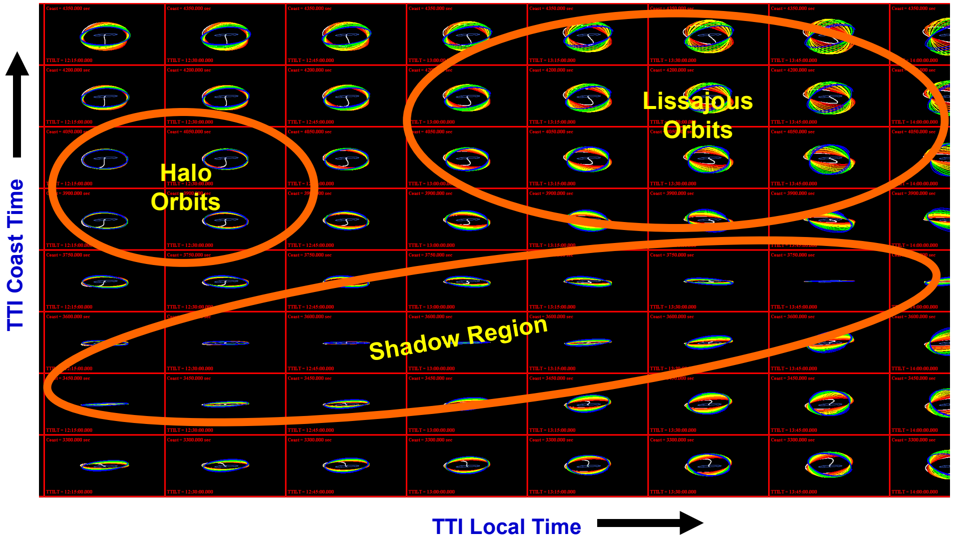




Orbit Considerations

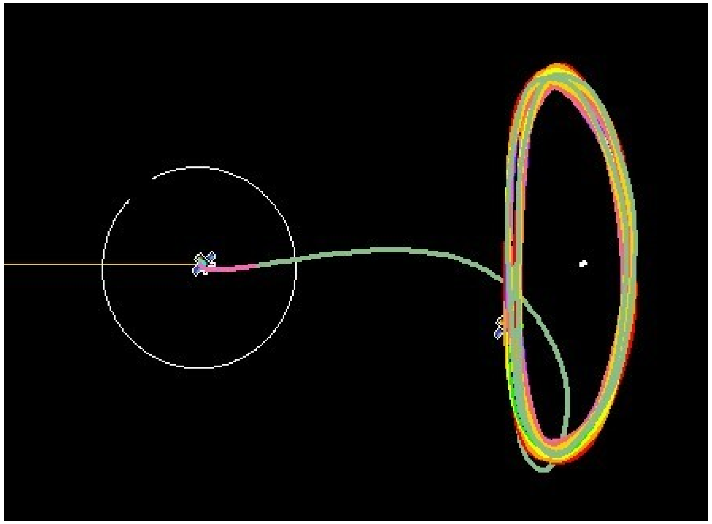


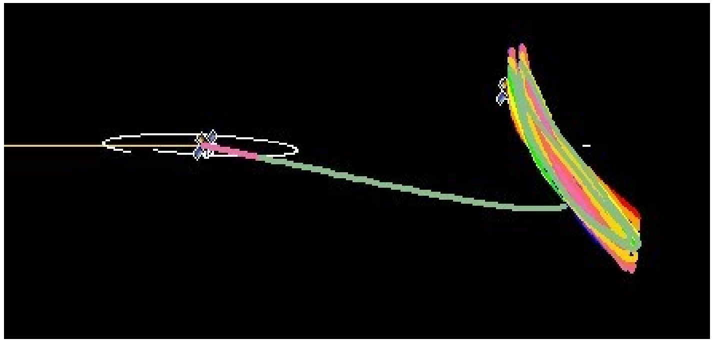
Courtesy Mark Beckman, JWST



- Orbit type varies as a function of launch time within a day
- The greater an L2 orbit's amplitude, the less insertion delta-v is required
- Insertion orbit selected to maximize launch opportunities
  - The size of the smallest achievable "zero-insertion-delta-v" orbit is a function of launch date
  - Frequent launch opportunities exist for "zero-insertion-delta-v" 800,000 km orbits (several opportunities every week)
  - ~1-2 launch opportunities per year for "zero-insertion-delta-v" 700,000 km orbits

- Baseline Orbit: 700,000 km "Y" semi-major axis L2 orbit

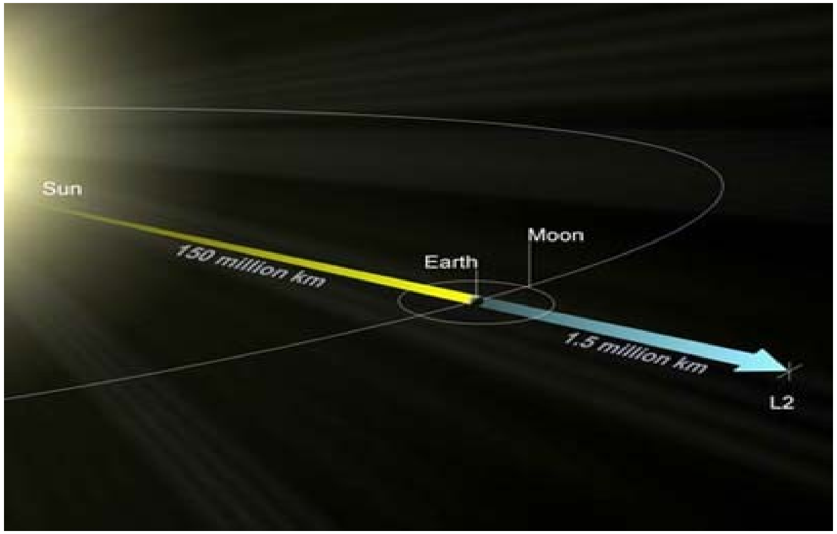




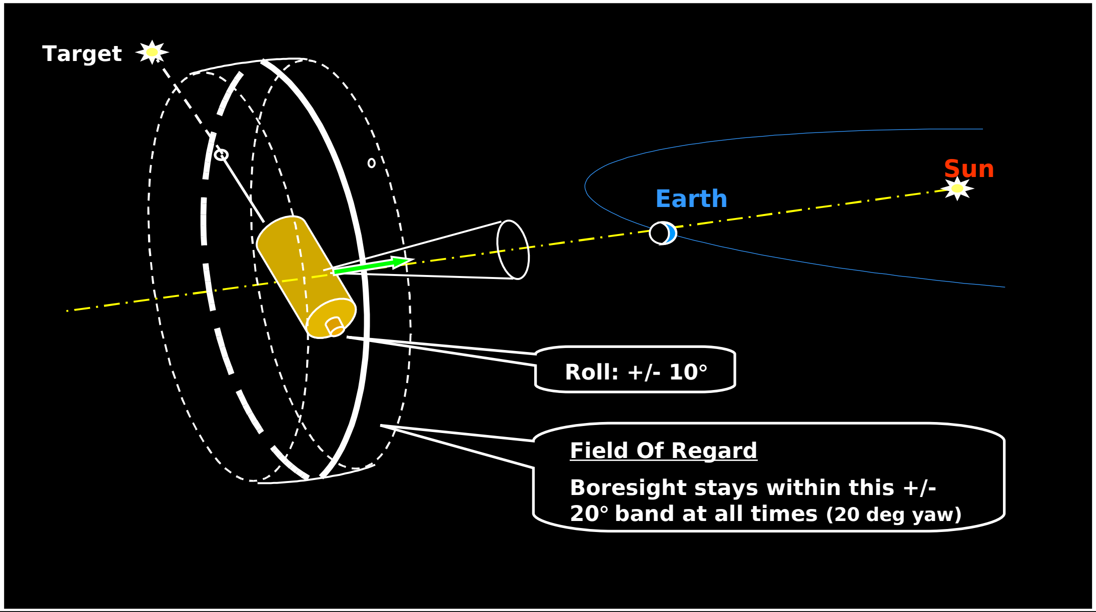
- Orbit mostly inside Earth's Magnetosheath
  - Lower low energy particle flux (solar wind)
- No Earth shadows during length of mission at L2
  - Potential of lunar penumbra at < 14% obscuration
- L2-Earth-SC Angle varies from 7° to 30° over 10 years

Mission Timeline

- **Launch (L) at T0**
  - Instruments and Cryo completely deenergized, Spacecraft power in Launch Mode (low power)
- **Transfer Trajectory Insertion (TTI) at L + 25 to 120 minutes**
  - Performed by LV Second Stage
- **LV Separation: TTI + 5 minutes**
  - LV 2nd stage Collision and Contamination Avoidance Maneuver
  - LV separation, Observatory in Acquisition Mode; acquire Sun-positive nominal attitude
  - Need live RF Comm w/ ground (have TDRSS capability)
- **Deploy Solar Arrays & High Gain Antenna**
- **Spacecraft full power on**
  - Some portions of Payload on, Cryo off
- **Commence Observatory Checkout**
- **ELV Dispersion Corrections at TTI + 24 hours**
- **Deploy Metering Structure**
- **Commence Instrument Aliveness Checks**
- **Observatory Outgas**
  - At least 2 weeks
- **First Mid-Course Correction: TTI + 16 days**
- **Instrument internal background measurement**
- **Jettison / Open Flight Mirror Assembly Covers, turn Cryo on**
- Open Instrument Covers and Gate Valves
- Calibrate w/ Celestial Targets
- Second Mid-Course Correction: TTI + 60 days
- L2 Orbit Insertion (L2OI) / Y-Amplitude Lowering Maneuver: ~ TTI + 100 days
- Science Ops
  - Downlink data (while observing, 30 minutes a day)
  - Repoint as required
  - Momentum Unloading Burns and L2 Stationkeeping burns during slews
  - Switch Instrument Mode every 2 weeks to 1 month
- EOM Disposal: L + 10 years +++ …
  - Delta-v < 1 m/s to driftaway trajectory, optional (not required)



IXO Observation Parameters



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 (goal value; negotiable, based on Reaction Wheel selection) ▪ Average # of slews per day: 2.5 during first year of mission, less later
Operational Efficiency	▪ ~85%, when averaged over the mission life
Timing accuracy	▪ Photon arrival tagged to UTC to $\pm$ 100 μ sec

IXO Pointing Performance

Term	Definition	Requirement	Stat
Image Position Control	The absolute precision of placing and keeping an image on the Focal Plane Detector	• Pitch: 10 arcsec • Yaw: 10 arcsec • Roll: 30 arcsec – Allocate 5 ["RSS"] of the 10" total to the ACS – Allocate 8.6 arcsec ["RSS"] for all other effects: thermal distortion, flex body effects (shear, banana, torsion), alignment shifts, etc	3σ
Image Position Reconstruction Knowledge (a.k.a.: "Aspect Reconstruction)	The absolute post facto knowledge of a down-linked and processed 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	HPD
Metering Structure Deflections (All Static and Dynamic Flex Body Effects combined)	Flex Body Effects displace images from their nominal position. Flex Body Effects are Static (e.g. deployment position errors) and Dynamic.	• < +/-10 mm in X and Y • < 4 arcmin in Torsion	(3σ)
Deployable Metering Structure Deflections (Static and Dynamic Flex Body Effects combined)	As above	• < +/-7 mm • < 3 arcmin in Torsion	(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	HPD

IXO Mass Rackup

ITEM	CBE	Reserve	Alloc.
Optics Module (OM)	2016	30%	2621
Fixed Metering Structure (FMS)	491	30%	638
Spacecraft Bus (SCB)	673	30%	875
Deployable (Aft) Metering Structure (10.6m)	408	30%	530
Instrument Module	695	30%	903
PAF and LV Separation System	227		241
OBSERVATORY DRY LAUNCH MASS	**4509**		**5808**
Propellant Mass (10 Years)			308
OBSERVATORY WET LAUNCH MASS			**6116**
Atlas V 551 Med Fairing Contractual Throw Mass			6425
Project Margin			309
Project Margin %			5%

THIS IS GOOD NEWS!!!

Propellant Calculations

DELTA V BUDGET FOR 5 YEARS				
	Estimate	ACS Tax	Contingency	Subtotal
Launch Window	10 m/sec	5%	0%	11 m/sec
ELV Dispersion Correction	40 m/sec	5%	0%	42 m/sec
Mid-Course Correction	10 m/sec	5%	5%	11 m/sec
Orbit Lowering Maneuver	25 m/sec	5%	0%	26 m/sec
L2 Stationkeeping for 5 years	20 m/sec	5%	5%	22 m/sec
Momentum Management for 5 years	1.8 m/sec	0%	5%	2 m/sec
De-orbit	1 m/sec	5%	5%	1 m/sec
			Total Equivalent Delta V	115 m/sec

ALLOCATION PROPELLANT BUDGET	
	Allocation
Allocation Dry Mass	5574.9 kg
Prop Mass (use equivalent Isp =275)	241.9 kg
5% Ullage and Residual	12 kg
Allocated Propellant Mass	254.0 kg

DELTA V BUDGET FOR 10 YEARS				
	Estimate	ACS Tax	Contingency	Subtotal
Launch Window	10 m/sec	5%	0%	11 m/sec
ELV Dispersion Correction	40 m/sec	5%	0%	42 m/sec
Mid-Course Correction	10 m/sec	5%	5%	11 m/sec
Orbit Lowering Maneuver	25 m/sec	5%	0%	26 m/sec
L2 Stationkeeping for 10 years	40 m/sec	5%	5%	44 m/sec
Momentum Management for 10 years	3.6 m/sec	0%	5%	4 m/sec
De-orbit	1 m/sec	5%	5%	1 m/sec
			Total Equivalent Delta V	139 m/sec

ALLOCATION PROPELLANT BUDGET	
	Allocation
Allocation Dry Mass	5574.9 kg
Prop Mass (use equivalent Isp =275)	293.7 kg
5% Ullage and Residual	15 kg
Allocated Propellant Mass	308.4 kg

Propellant mass increase is about

11 kg/year

Power Loads

2008 ConX-5 MDL Study's Power 2008 08 15 GK

(CBE + 30%)	Launch	Cruise	Science	Downlink	Slew	Safehold	Peak
Observatory	164	3496	3537	3570	3828	2680	4344
Science Payload	0	2874	2874	2874	2797	1897	2874
S/C	164	622	663	696	1031	783	1470
ACS	16	65	70	70	433	57	569
C&DH	98	192	192	203	205	185	229
RF Comm	0	57	57	104	57	57	117
Mech	0	0	0	0	0	0	0
Propulsion	6.5	6.5	6.5	6.5	6.5	6.5	6.5
Power	5	185	217	219	210	175	305

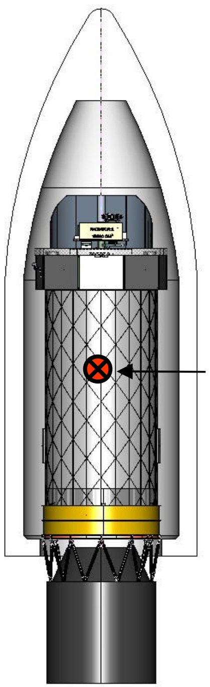
CBE Numbers	Mode 1		Mode 2		Safehold	Unit Power		
	Ave	Peak	Ave	Peak		Ave	Peak	Standby
Science Payload	2152	2211	2017	1955	1459			
FMA	1394	1394	1394	1394	1394	1394	1394	1394
XMS	649	701	323	215	65	649	701	323
WFI	47	47	211	250	0	211	250	47
HXI	5	5	32	32	0	32	32	5
XGS	57	64	57	64	0	57	64	0

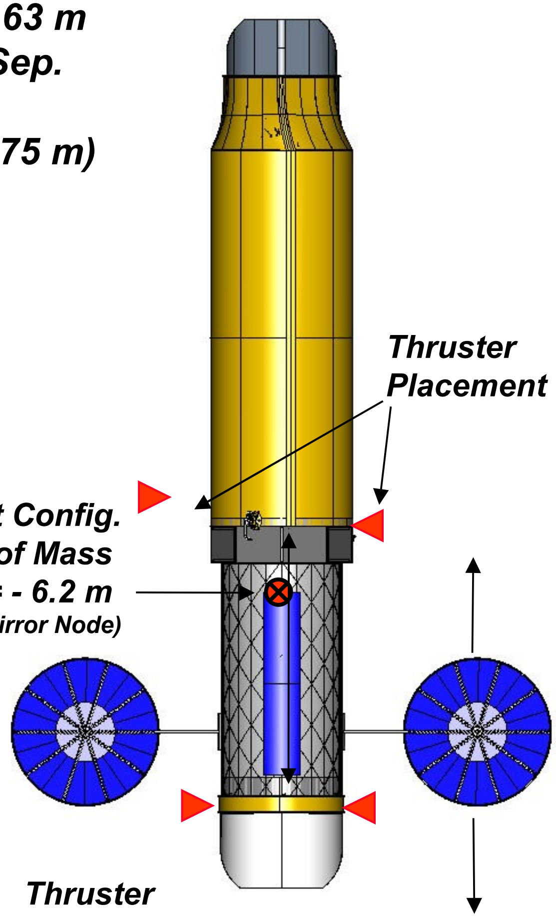
- *PSE BOL power delivered is the max. EOL load + 20% = 5000W (sized for 10 years L2 mission)*

ISSUES

- Current configuration doesn't self-consistently address hard x-ray capability
- Only one of the two potential gratings configurations was studied
- Need to re-visit data rates with backgrounds
- Baffle layouts are generic
- Additional study of micrometeorite issue is required
- There is a significant issue with CP/CM offset (see next slide)

CM Considerations





Three "Center of Mass" (CM) considerations:

2. Launch Vehicle "CG height limitation"
   - Height limit of CG in Atlas 551 using a "3302" Truss Payload Adapter: 571.5 cm above Separation Plane
3. Propulsion thrust vector
   - Must locate all thrusters on non-deployable parts of the Observatory (welded prop system)
   - CM must be "embraced" by thrusters "above and below"
   - Thrusters must be as far apart as possible for large "slew" moment arm
4. Center of Mass – Center of (solar) Pressure
   - Minimizing CM-CP offset:
     - by proper positioning the solar arrays on the Fixed Metering Structure…

     minimizes:
     - solar torque disturbance
     - propellant and frequency of momentum unloading

Low Risk Mission Approach

The Spacecraft (i.e. Observatory minus Science Payload) has numerous features to guarantee mission success:

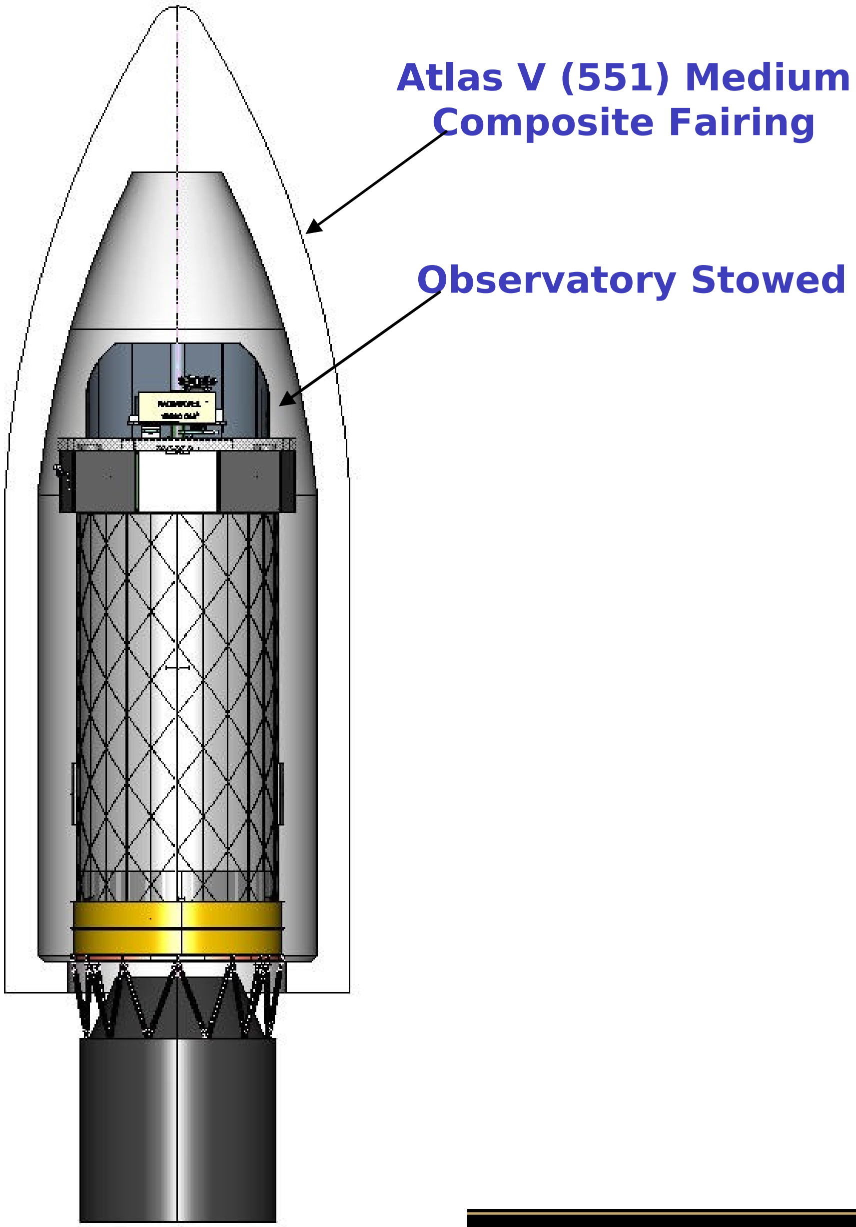
- Class B Mission
  - No significant performance degradation w/ single point failure
- Credible Deployable Mast performance
  - Performance analyzed with existing Nustar-like booms (20m focal length); static pointing performance meets and outperforms IXO needs
- Failsafe mechanisms
  - Slightly degraded mission possible w/ only 2 of 3 masts deployed
  - Failsafe Moveable Instrument Platform mechanism enables actuation even upon failure of the primary mechanism
- C&DH
  - Ultra redundant “spacecraft wide web” Spacewire architecture
- Robust “no-microprocessors” Sun-positive Safe-Mode
  - Body mounted solar arrays allow the Observatory to maintain Survival Mode indefinitely even w/o deployed solar array wings

Summary and Future Work

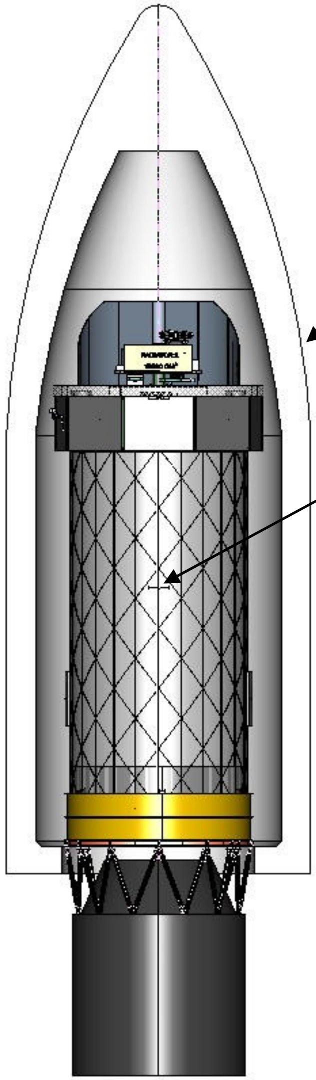
- Baseline mission concept appears viable
  - Spacecraft (i.e. Observatory minus Science Payload) appears feasible with technologies that exist today
- Work is continuing by refining the design in every discipline with recursive iteration thru all system implications until full convergence:
  - Finite Element Modeling (launch and on-orbit configurations) to validate mass estimates
  - Control System requirements definition (full science requirements flow-down) and performance analysis
  - Alignment Monitor definition and accommodation
  - Component layout, both Spacecraft and Science Payload
- Future mission configuration work is anticipated to address
  - 20 vs. 25 m focal length trades
  - Payload modifications to achieve hard X-ray response
  - Compatibility with micropore mirror
  - Compatibility with Ariane V launch vehicle
- CDF’s independent study should provide additional confidence in the overall approach

BACKUP MATERIAL

IXO Observatory - Launch Configuration



Launch Configuration



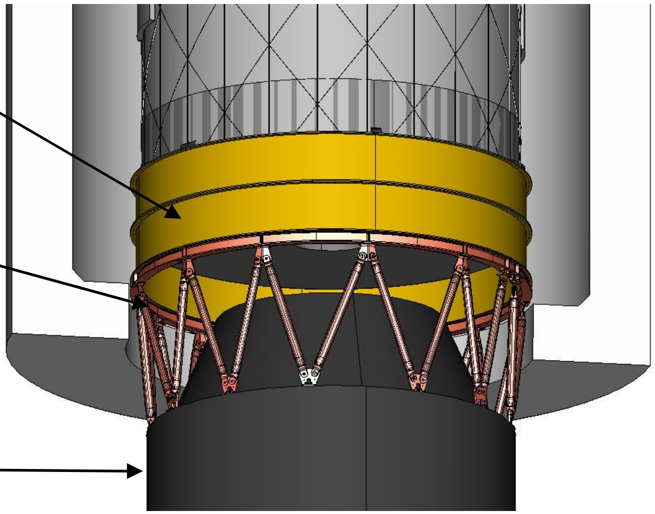
Atlas V
(551)
Medium
Composite
Fairing

Observator
y in Stowed
Configurati
on

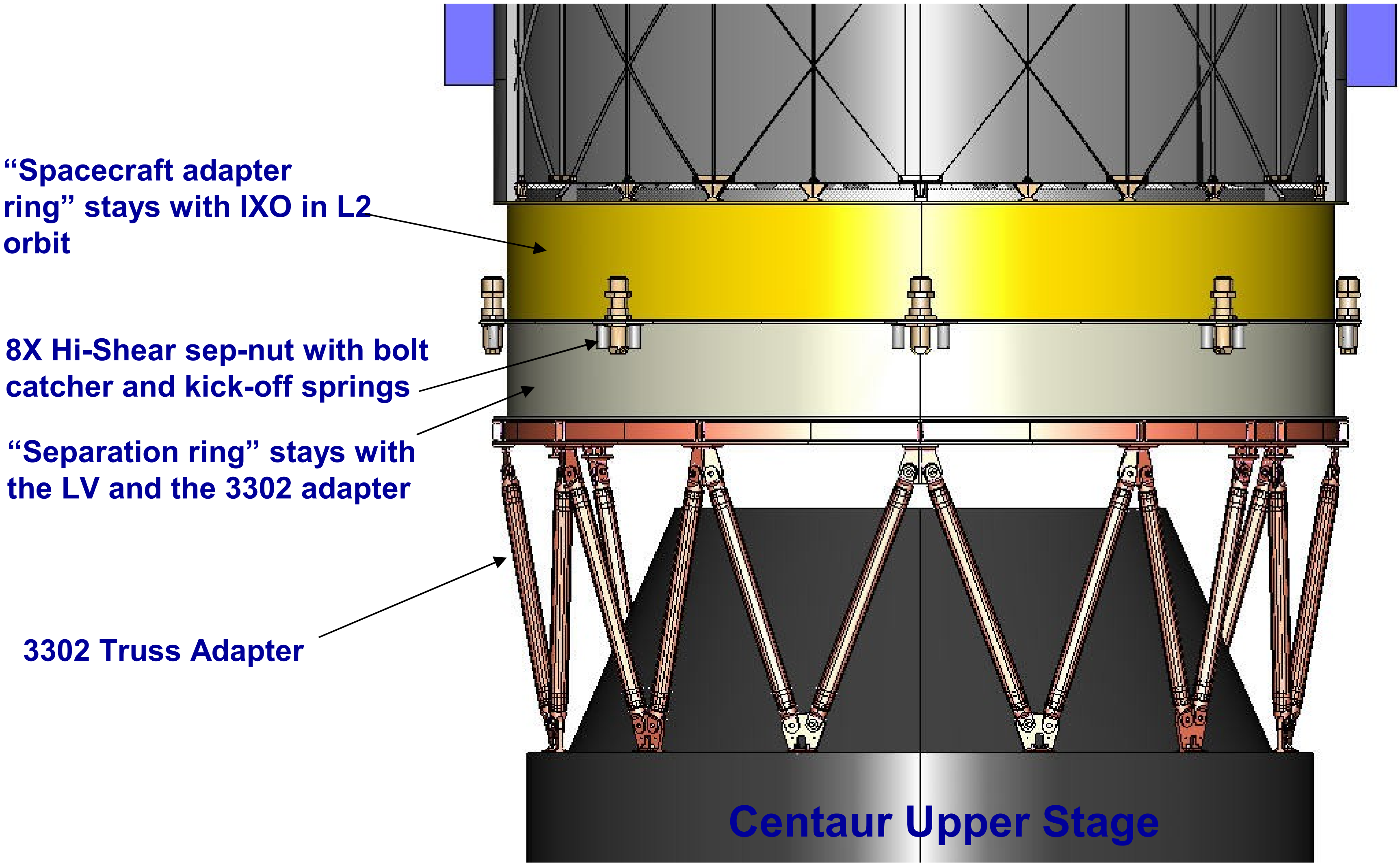
Encapsulati
on I/F Ring

“3302”
Truss
Payload
Attachment
Fixture

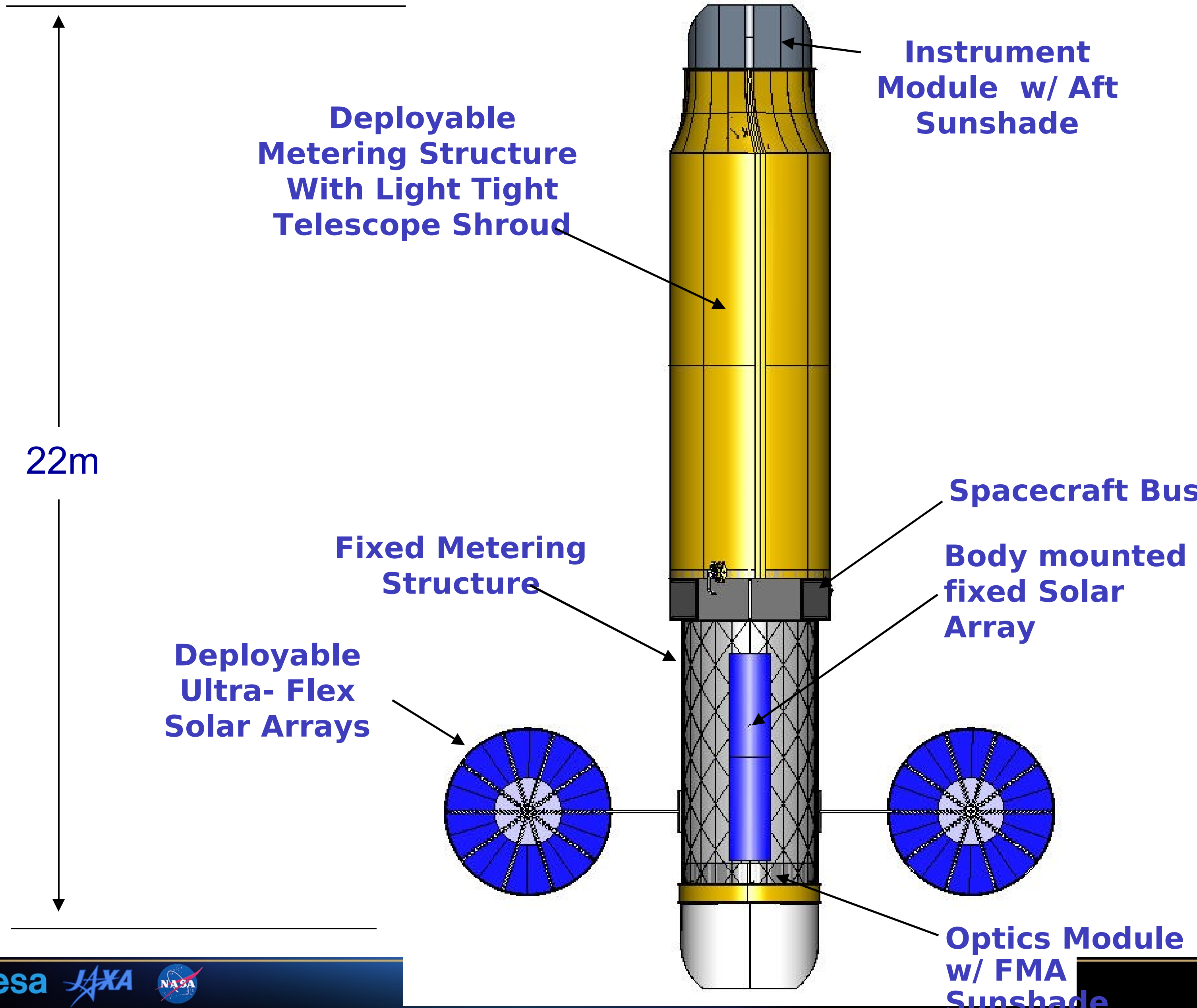
Centaur
(Atlas V’s
2nd Stage)



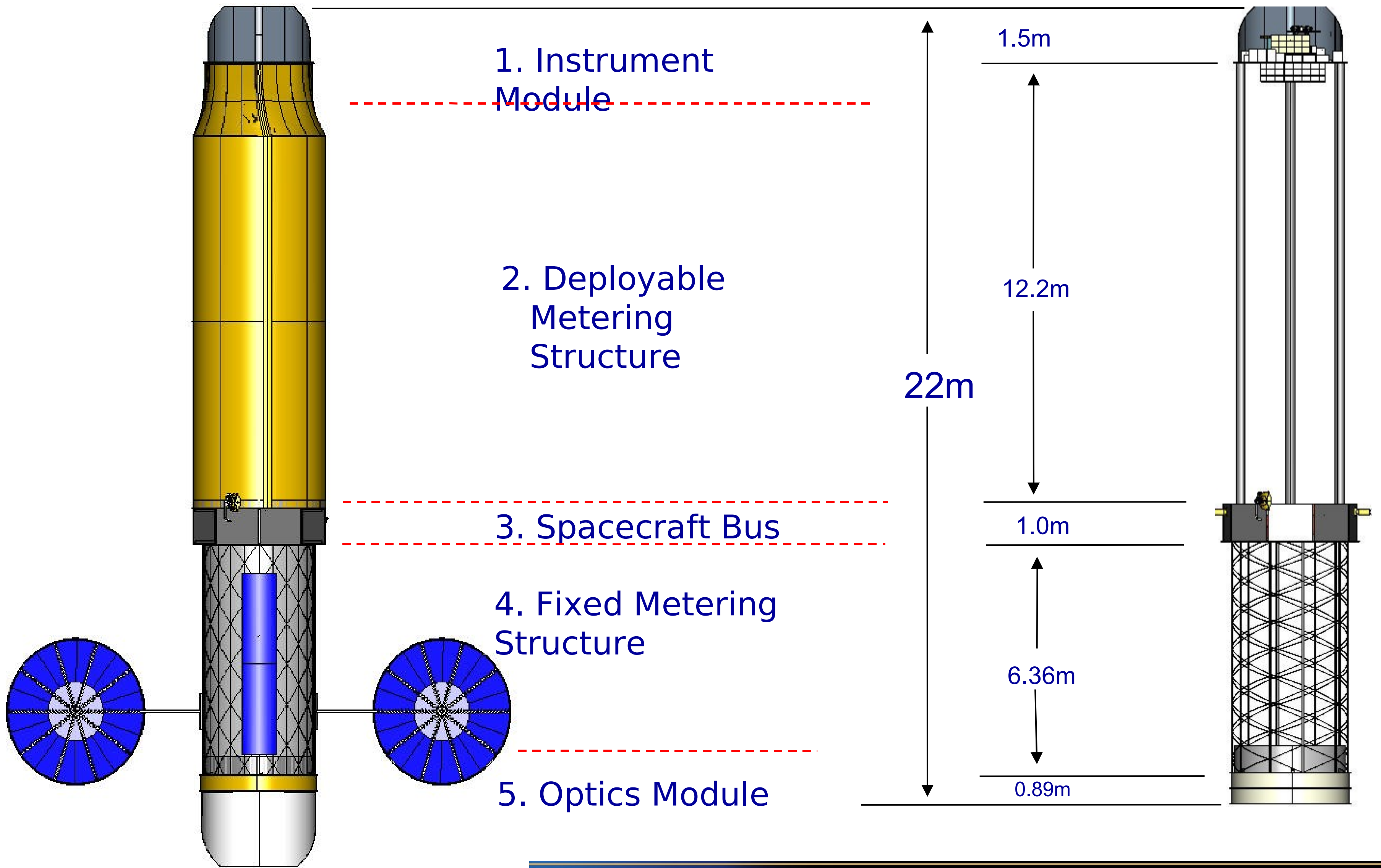
Launch Vehicle Truss Adapter and Mission-unique Separation System



IXO Observatory - Deployed Configuration



Modular Observatory Design



2. Deployable Metering Structure Parameters

All numbers apply to 3 Mast System Deployed	Term Combined for deployment, short term, and long term effects. Thermal distortion not included	Parameters	Unit	Stat
Dimensions	Length	12.2	m	
Deployable Metering Structure Deflections (Static and Dynamic Flex Body Effects combined)	Flex Body Effects displace images from their nominal position (i.e. alter the pointing of the Boresight, defined as the line connecting a "central" pixel to the Mirror Node)	< +/- 1.5	mm	(3σ)
Frequencies	1st mode (torsion) 2ed mode (bending)	> 1 > 2	Hz Hz	
Mass	Incl. complete 3 Mast System, Internal Harnesses, Deployment Controller, etc.	< 200	kg	
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	

2. Deployable Metering Structure - Long Term Drift and Repeatability

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

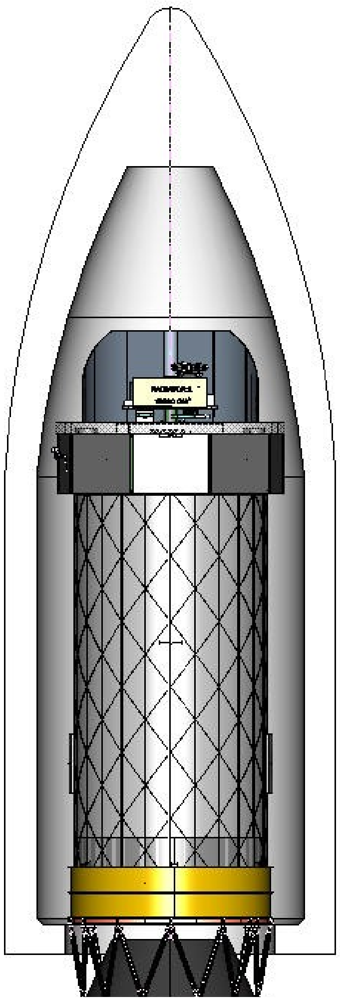
From: Messner, Dave [Dave.Messner@ATK.COM), Sunday, August 03, 2008 10:44 PM

- **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 one mast, (mm)**
  - **0.558 mm 3σ 3 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 one 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.

Launch Configuration and Mass Summary



Atlas V 551
Medium Composite Fairing

Payload	Estimate (kg)	Cont.	Allocation (kg)
Flight Mirror Assembly	1775	30%	2308
XMS	258	30%	336
WFI	80	30%	104
XGS	62	30%	81
HXI	24	30%	31
Misc. Payload Accom	51	30%	66
Payload Total	**2250**	**30%**	**2924**
Bus	**Estimate (kg)**	**Cont.**	**Allocation (kg)**
Avionics	66	30%	86
Communications	36	30%	47
Attitude Control	72	30%	94
Structure and Mechanisms	1188	30%	1545
Power	108	30%	141
Propulsion (dry)	48	30%	63
Thermal	239	30%	311
Harness	274	30%	357
Bus Total	**2033**	**30%**	**2643**
Observatory	**Estimate (kg)**	**Cont.**	**Allocation (kg)**
Observatory On Orbit Dry Mass	4282	30%	5567
Separation System LV Side	227	6%	241
Propellant Mass (10 yrs)			308
Observatory Wet Launch Mass			**6116**
Margins			
Atlas V 551 Throw Mass (C3=-0.5)			**6425**
Project Manager's Margin			**309**

5 % margin

Data Summary

Element		Data Rate (kbps) (Includes 30% contingency)		
		Average	Peak	Comments
FMA	Science	0.0	0.0	
	Housekeeping	1.3	1.3	
	Total FMA	**1.3**	**1.3**	
XMS	Science	52.0	2,184.0	
	Housekeeping	1.3	1.3	
	Total XMS	**53.3**	**2,185.3**	
WFI	Science	58.5	585.0	4.5 Mbps for high background;
	Housekeeping	1.3	1.3	
	Total WFI	**59.8**	**586.3**	
HXI	Science	17.0	150.0	based on BEPAC HXT
	Housekeeping	1.3	1.3	
	Total HXI	**18.3**	**151.3**	
XGS	Science	150.0	1,500.0	
	Housekeeping	1.3	1.3	
	Total XGS	**151.3**	**1,501.3**	
Total by Mode	Mode 1	**204.6**	**3,686.6**	
	Mode 2	**229.4**	**2,238.9**	

STORAGE MODE 1	Rate	Unit
Low Science Data Rate per sec	204.6	kbps
Low Science Data Rate - Data Volume per hour	0.7	Gbit
Low Science Data Rate - Data Volume per day	17.7	Gbit
Low Science Data Rate - Data Volume per 60 hours	44.2	Gbit
High Science Data Rate per sec	3,686.6	kbps
High Science Data Rate - Data Volume per hour	13.3	Gbit
High Science Data Rate - Data Volume per 12 hours	159.3	Gbit
Mode 1 Storage Total	**203.5**	**Gbit**

STORAGE MODE 2	Rate	Unit
Low Science Data Rate per sec	229.4	kbps
Low Science Data Rate - Data Volume per hour	825.8	Gbit
Low Science Data Rate - Data Volume per day	19.8	Gbit
Low Science Data Rate - Data Volume per 60 hours	49.6	Gbit
High Science Data Rate per sec	2,238.9	kbps
High Science Data Rate - Data Volume per hour	8.1	Gbit
High Science Data rate 12 hours	96.7	Gbit
Mode 2 Total	**146.3**	**Gbit**

Science Modes

Switch between Mode 1 and 2 on average 2 times per month (based on use of XMS and WFI). Targets available for < 12 weeks per year based on ± 20 deg pitch field of regard.		Science Modes	
		Mode 1	Mode 2
Instrument Operations	Science	XMS, XGS	WFI, HXI, XGS
	Standby	WFI, HXI	XMS
Observation Duration	Average	10 hours	
	Minimum	30 minutes	
	Peak	48 hours	
Percent of time for each Mode		50%	50%

Systems Engineering

- **Systems engineering practices based on the following guidelines**
  - NASA Systems Engineering Handbook, SP-610S
  - GSFC Systems Engineering GPR 7120.5A
  - GSFC "GOLD Rules" (GSFC – STD – 1000, Rules for the Design, Development, Verification, and Operation of Flight Systems)

- **Class B Missions**
  - Single Point Failures (SPFs)
    - Critical SPFs (for Level 1 requirements) may be permitted but are minimized and mitigated by use of high reliability parts and additional testing. Essential spacecraft functions and key instruments are typically fully redundant. Other hardware has partial redundancy and/or provisions for graceful degradation.
  - Engineering Model, Prototype, Flight, and Spare Hardware
    - Engineering model hardware for new or significantly modified designs. Protoflight hardware (in lieu of separate prototype and flight models) except where extensive qualification testing is anticipated. Spare (or refurbishable prototype) hardware as needed to avoidmajor program impact.
  - Qualification, Acceptance, and Protoflight Test Program
    - Formal qualification and acceptance test programs and integrated end-to-end testing at all hardware levels. May use a combination of qualification and protoflight hardware. Qualified software simulators used to verify software and system.