SLS launched missions concept studies for LUVOIR Mission

MSFC Advanced Concepts

National Aeronautics and Space Administration

Potential Decadal Missions:

- FAR IR Surveyor
- Habitable-Exoplanet Imaging Mission
- Large UV/Optical/IR Surveyor
- X-ray Surveyor

y

Astrophysics

Paul Hertz

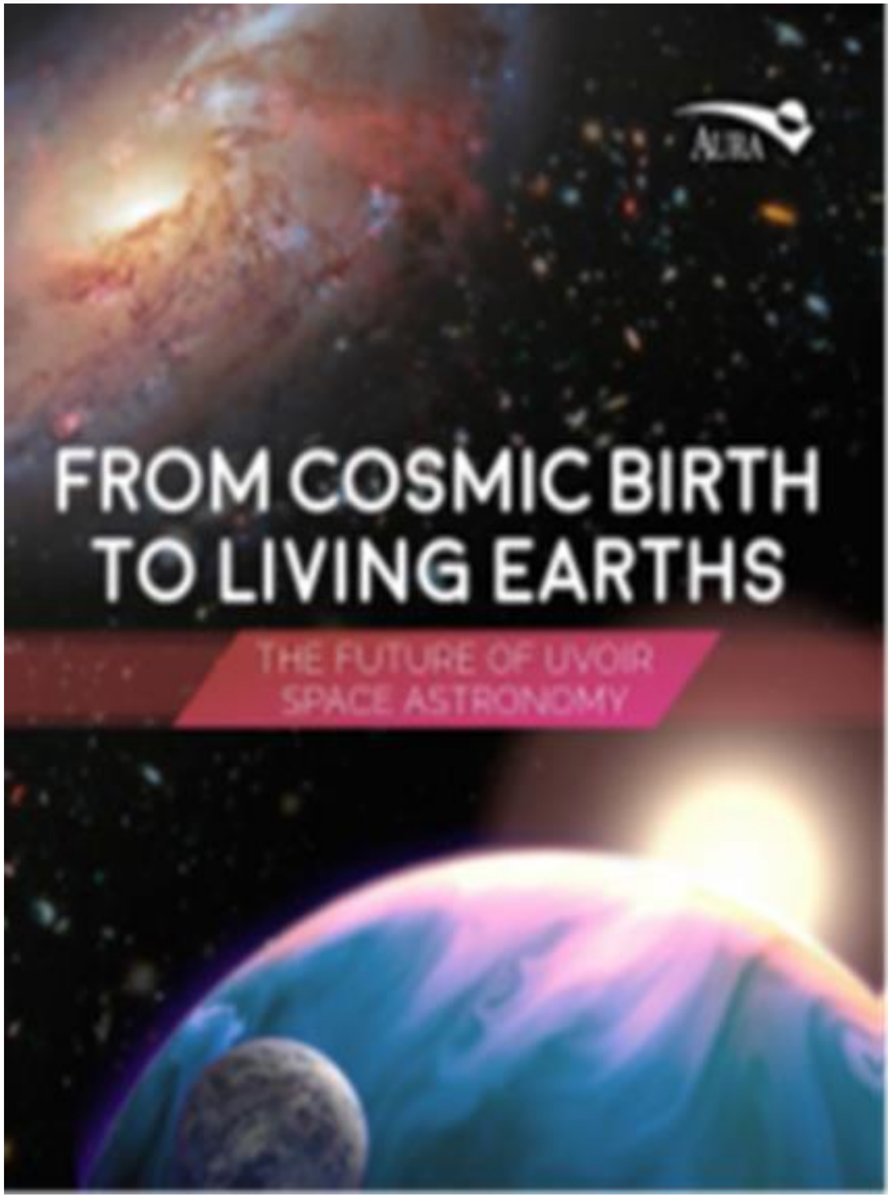
Director, Astrophysics Division
Science Mission Directorate
@PHertzNASA

www.nasa.gov

AURA
“Cosmic Birth to Living Earth”

The AURA “Cosmic Birth to Living Earth” Report calls for a

10 meter class space telescope with sufficient stability and instrumentation to make very significant advances in both Exoplanet and General Astrophysics



AURA

FROM COSMIC BIRTH TO LIVING EARTHS

THE FUTURE OF UVOIR SPACE ASTRONOMY

ATLAST-12
an SLS Mission Concept

The MSFC Advanced Concept Office performed a preliminary mission concept study during February/March 2015.

The starting point for the Study were MSFC's 2007 ATLAST-6 and 2009 ATLAST-8 studies.

- Assumed same instruments as ATLAST-8.
- Used ATLAST-8 spacecraft as point of departure.

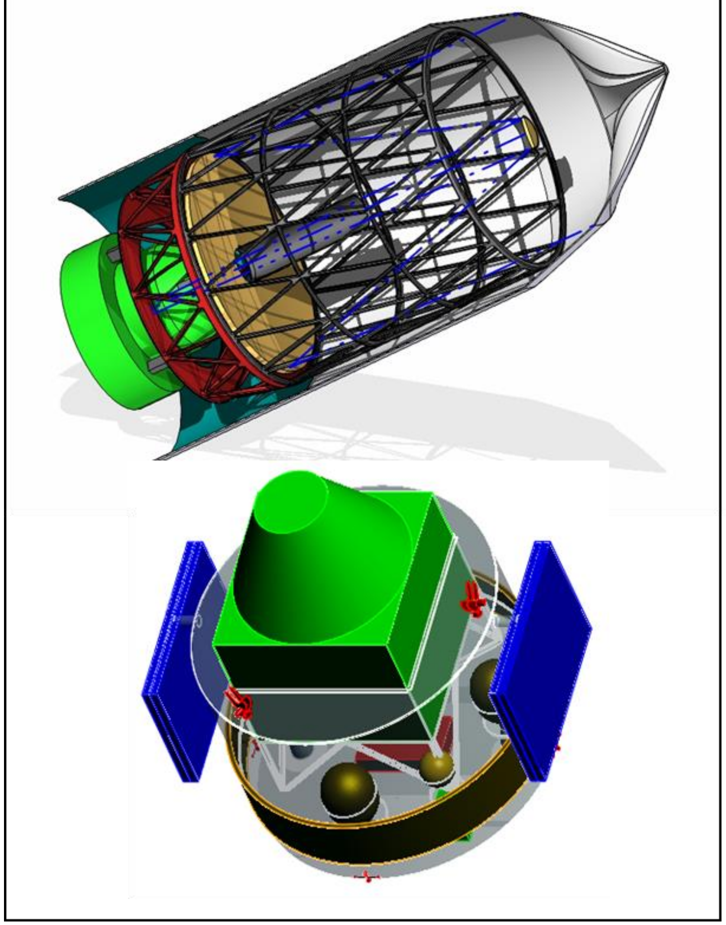
The Study was out-briefed on 17 March 2015.

These charts are selected from the 133 chart Study report.

DISCLAIMER: This is a preliminary study of a notional design. Several more iterations are required.

ATLAST-6 & ATLAST-8 Studies

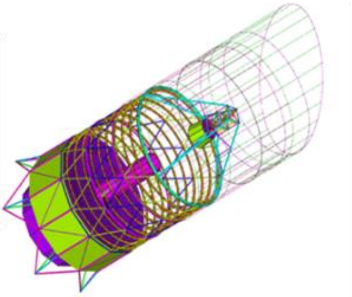
2007
6-meter telescope study



2008
NASA ROSES proposal award
ATLAST
(Advanced Technology Large Aperture Space Telescope)
- Space Telescope Science Institute
- MSFC
- GSFC
- JPL


ARES V

2009
Spacecraft Design Study



Astro2010 Decadal Survey

Postman, Marc, et. al., "A Large Monolithic-Aperture Optical/UV Serviceable Space Telescope Deployed to L2 by an Ares-V Cargo Launch Vehicle", Science Associated with Lunar Exploration Architecture, Tempe, AZ Feb. 28, 2007

Stahl, H. Philip, Marc Postman, William R. Arnold, Sr., Randall C. Hopkins, Linda Hornsby, Gary E. Mosier, and Bert A. Pasquale, "ATLAST-8 Mission concept study for 8-meter Monolithic UV/Optical Space Telescope", SPIE Proceedings 7731, 2010, DOI:10.1117/12.856256

ATLAST-6 & ATLAST-8 Studies

Astro2010 Decadal Survey Whitepaper and RFI2

Advanced Technology Large-Aperture Space Telescope (ATLAST)

Appendix C: ATLAST-8m Design & Engineering Study

The ATLAST-8m engineering study was lead by NASA MFSC with guidance from the Space Telescope Science Institute and collaboration from team members NASA GSFC, NASA JPL, Northrop-Grumman, and Ball Aerospace. Additional support was provided by the University of Alabama in Huntsville, ATK and Schott Glass.

Cut-away (and simulated) view of an Ares V launch vehicle containing the ATLAST-8m payload

> "Recommendation: NASA should conduct further study of the following missions concepts, which have the most potential to demonstrate the scientific opportunities provided by the Constellation System: 8-meter Monolithic Space Telescope", page 3.
>
> "The 8-Meter Monolithic Space Telescope offers the possibility of a relatively easy and faster scientific use of the Ares V launch vehicle compared with other, more complex telescope designs. The reason for this fast-track ability is the use of present-day, proven, low-cost (compared with lightweight space design) technologies", page 31

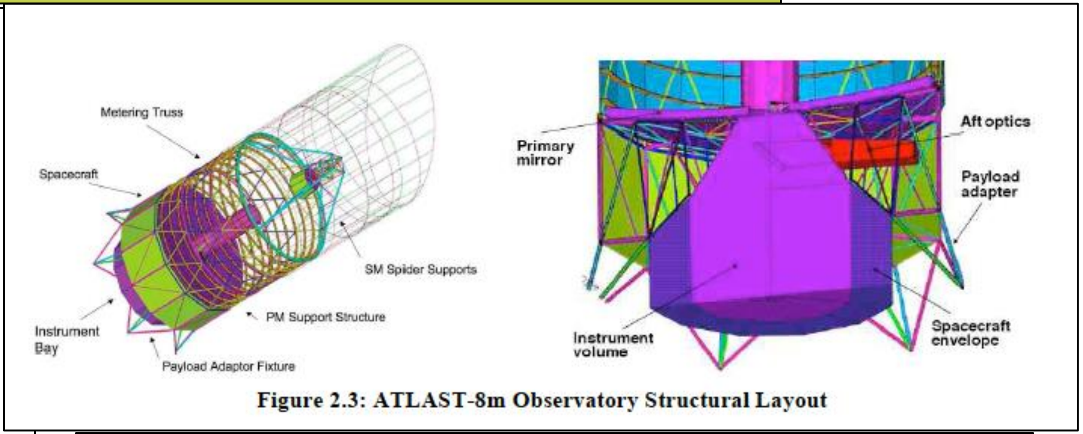
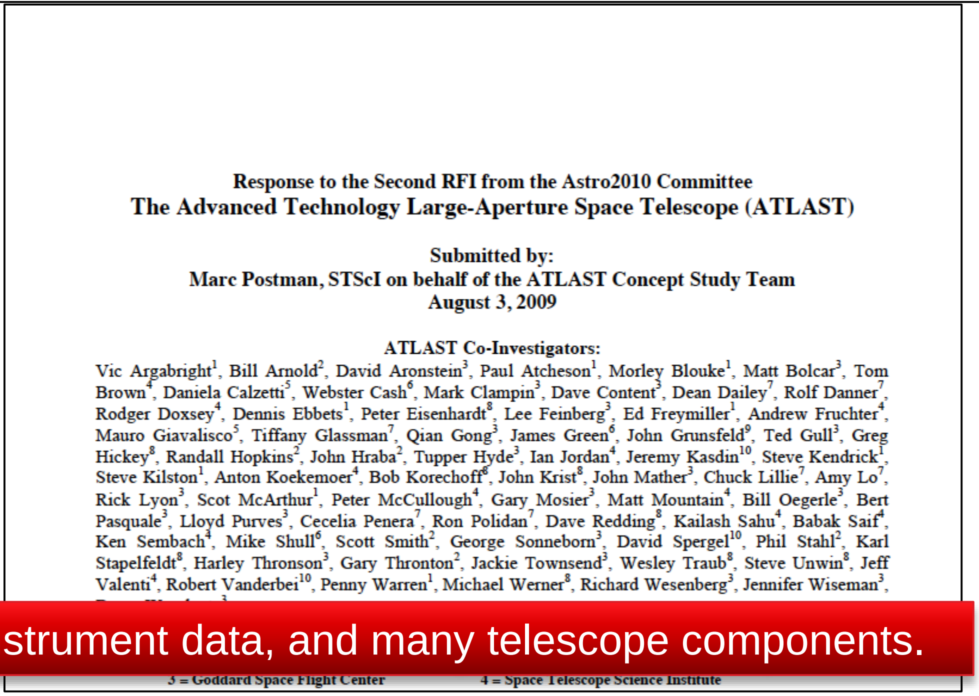


Figure 2.3: ATLAST-8m Observatory Structural Layout



Response to the Second RFI from the Astro2010 Committee
The Advanced Technology Large-Aperture Space Telescope (ATLAST)

Submitted by:
Marc Postman, STScI on behalf of the ATLAST Concept Study Team
August 3, 2009

ATLAST Co-Investigators:

Vic Argabright[1], Bill Arnold[2], David Aronstein[3], Paul Atcheson[1], Morley Blouke[1], Matt Bolcar[3], Tom Brown[4], Daniela Calzetti[5], Webster Cash[6], Mark Clampin[3], Dave Content[3], Dean Dailey[7], Rolf Danner[7], Rodger Doxsey[4], Dennis Ebbets[1], Peter Eisenhardt[8], Lee Feinberg[3], Ed Freymiller[1], Andrew Fruchter[4], Mauro Giavalisco[5], Tiffany Glassman[7], Qian Gong[3], James Green[6], John Grunsfeld[9], Ted Gull[3], Greg Hickey[8], Randall Hopkins[2], John Hraba[2], Tupper Hyde[3], Ian Jordan[4], Jeremy Kasdin[10], Steve Kendrick[1], Steve Kilston[1], Anton Koekemoer[4], Bob Korechoff[8], John Krist[8], John Mather[3], Chuck Lillie[7], Amy Lo[7], Rick Lyon[3], Scot McArthur[1], Peter McCullough[4], Gary Mosier[3], Matt Mountain[4], Bill Oegerle[3], Bert Pasquale[3], Lloyd Purves[3], Cecelia Penera[7], Ron Polidan[7], Dave Redding[8], Kailash Sahu[4], Babak Saif[4], Ken Sembach[4], Mike Shull[6], Scott Smith[2], George Sonneborn[3], David Spergel[10], Phil Stahl[2], Karl Stapelfeldt[8], Harley Thronson[3], Gary Thronton[2], Jackie Townsend[3], Wesley Traub[8], Steve Unwin[8], Jeff Valenti[4], Robert Vanderbei[10], Penny Warren[1], Michael Werner[8], Richard Wesenberg[3], Jennifer Wiseman[3],

3 = Goddard Space Flight Center 4 = Space Telescope Science Institute

Source of spacecraft mass estimates, science instrument data, and many telescope components.

STUDY OVERVIEW

LUVOIR (Large Ultra-Violet / Optical / Infra-Red) Telescope

General Assumptions

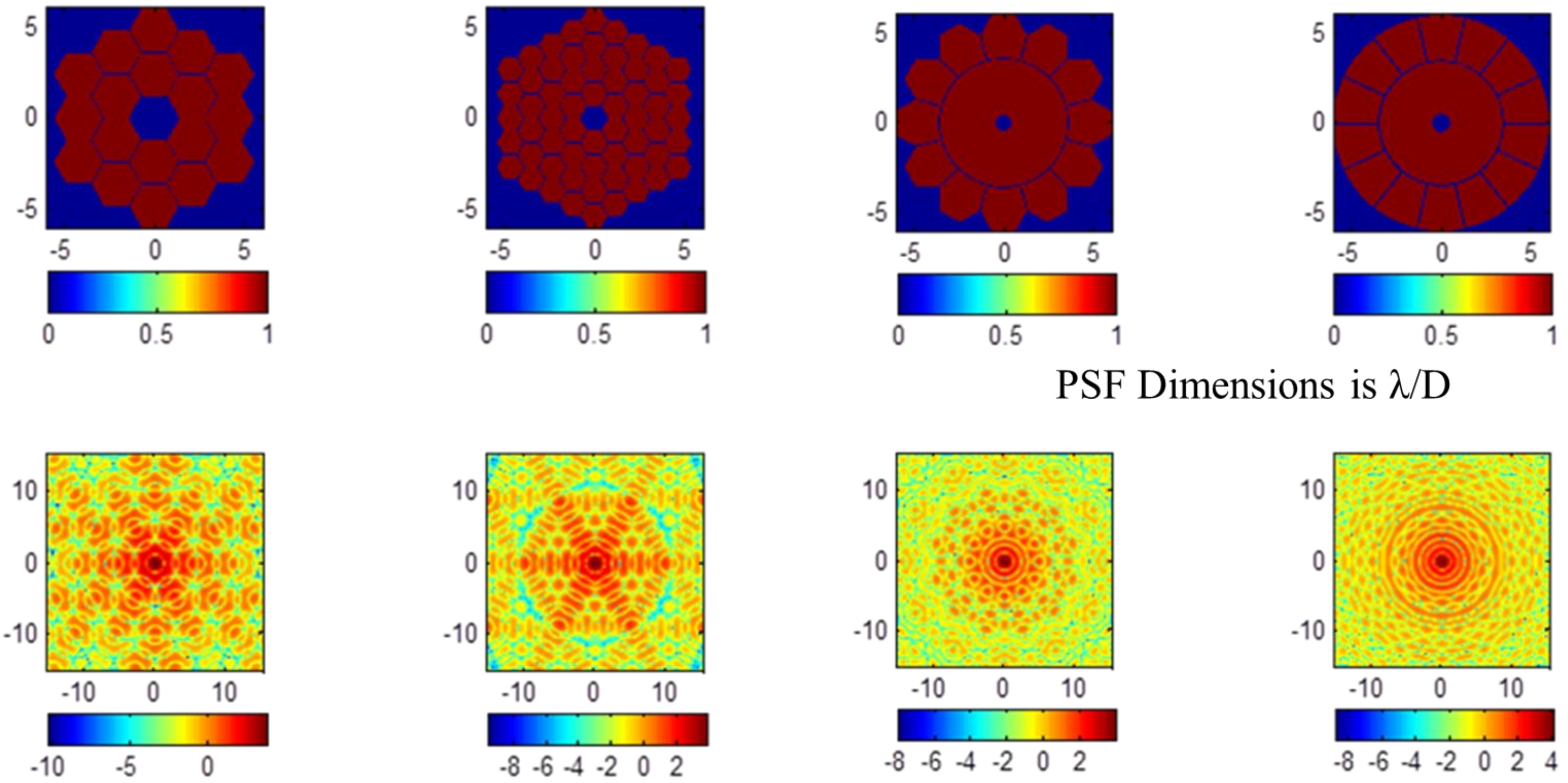
- General Astrophysics community wants a telescope aperture diameter > 8 meters
- Exoplanet Science requires a telescope with a wavefront that is stable at approximately 10 pico-meters per 10 minutes.

NOTE: while the required stability period is stated to be 10 minutes, wavefront needs to be stable to 10 pm between wavefront sense and control (WFSC) updates. This could be as short as 1 minute or longer than 30 minutes depending upon brightness of star being observed and WFSC technology.

From Cosmic Birth to Living Earths: the future of UVOIR Space Astronomy, 2015
Stahl, H. Philip Stahl; Marc Postman; Gary Mosier; W. Scott Smith; Carl Blaurock; Kong Ha; Christopher C. Stark, “AMTD: update of engineering specifications derived from science requirements for future UVOIR space telescopes”, Proc. SPIE. 9143, Space Telescopes and Instrumentation 2014: Optical, Infrared, and Millimeter Wave, 91431T. (August 02, 2014) doi: 10.1117/12.2054766
Stahl, H. Philip, Marc Postman and W. Scott Smith, “Engineering specifications for large aperture UVO space telescopes derived from science requirements”, Proc. SPIE 8860, 2013, DOI: 10.1117/12.2024480

Stahl Assumptions

- Circular aperture shape produces coronagraph friendly PSF
- Single ring of segments may yield smaller IWA (diffraction)
- Large center segment might provide a 'descope' path



PSF Dimensions is λ/D

Stahl, H. Philip Stahl; Marc Postman; Gary Mosier; W. Scott Smith; Carl Blaurock; Kong Ha; Christopher C. Stark, "AMTD: update of engineering specifications derived from science requirements for future UVOIR space telescopes", Proc. SPIE. 9143, Space Telescopes and Instrumentation 2014: Optical, Infrared, and Millimeter Wave, 91431T. (August 02, 2014) doi: 10.1117/12.2054766

Stahl Assumptions (continued)

Segment must fit inside 4-m (or 2.4-m) circular blank

Using 12 Segments from 4-m blanks

6-m core = 12 m aperture
8-m core = 13 m aperture

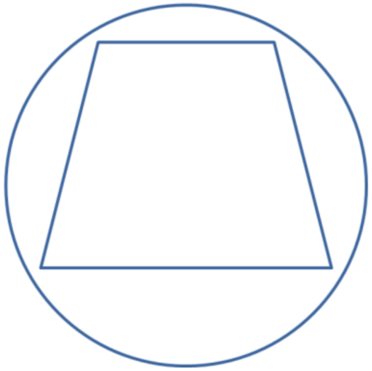
Using 18 Segments from 4-m blanks

6-m core = 13 m aperture
8-m core = 14.5 m aperture

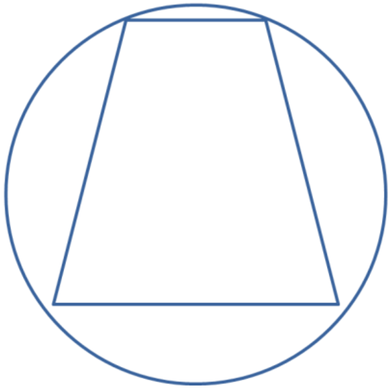
Using 24 Segments from 2.4-m blanks

6-m core = 10 m aperture
8-m core = 12 m aperture

13-m aperture
8-m Core, 12 2.5-m tall Segments



12-m Aperture
6-m Core, 12 3-m tall Segments

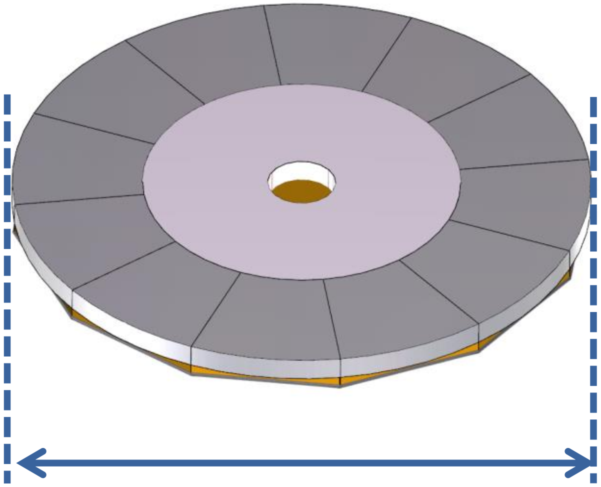


Instructions to Study Team

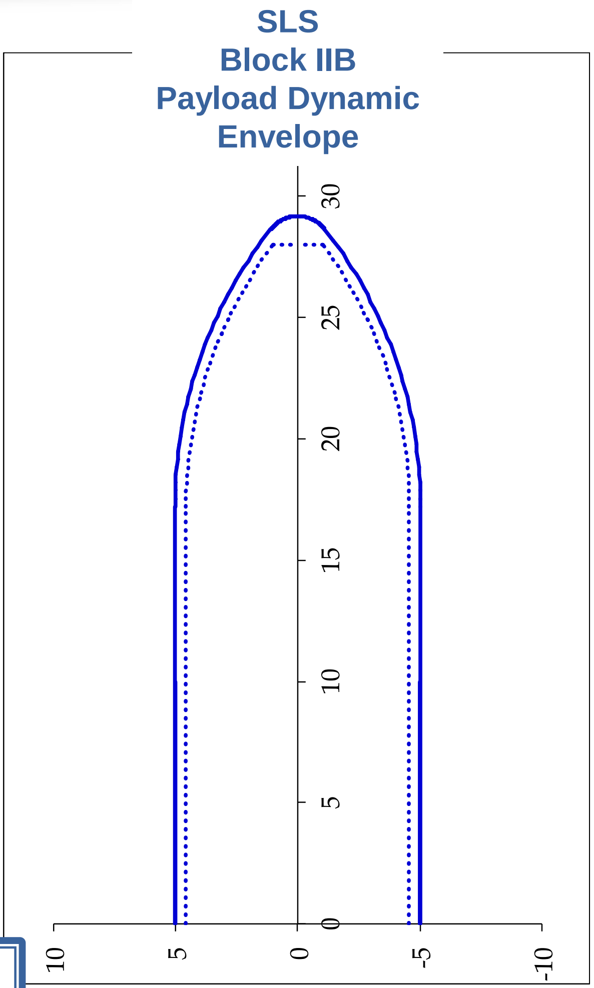
- Determine the largest diameter telescope with a center core and a single ring of segments that packages inside mass and volume of SLS.
- Since others are studying flat sunshade, we will study active-controlled heated scarfed tube sunshade.
- Primary Mirror Structure must have >20 Hz first mode.
- Primary Mirror Assembly shall have ~ 150 kg/m2 Areal Density.

ATLAST-12

ATLAST-12 is a 12.7-m observatory to be launched to SE-L2 on SLS Block II-B in 2035



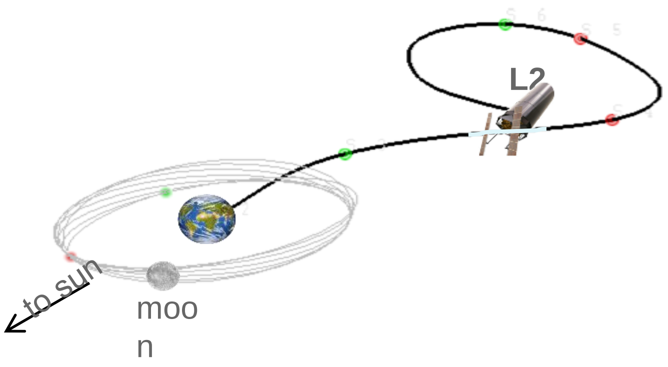
12.7 meter deployed diameter, with thickness of approximately 0.5 m


SLS Block IIB Payload Dynamic Envelope

Estimated Performance	
C3 (km^2/s^2)	Mass (mt)
-0.7	46.3

SLS Block II-B

- 10 meter fairing
- 46 mt to SE-L2



Mission Description	
Launch	SLS Block IIB, 2035
Orbit	Halo orbit about Sun-Earth L2 provides stable thermal environment, few obstructions.

Mission and Spacecraft Requirements (1 of 2)

Requirement	Value
Launch Year	2035
Launch Vehicle	SLS Block II-B
Mission Duration	30 years from launch
Deployment Time	Maximum of 6 months from launch to full capability
Service Philosophy	Design for servicing, using on-orbit replaceable units (ORUs)
Service Interval	5 years
Serviceable Component Lifetime	10 years
Orbit	Sun-Earth L2 halo orbit; servicing orbit TBD (observatory will maneuver to orbit in Earth-moon vicinity to allow servicing/instrument replacement)
Payload Description	Optical tube assembly; several instruments at focal plane behind primary mirror
Payload Power, total, w/o contingency	(see Basic Instrument Data slides for breakout)
Payload Mass, total, w/o contingency	(see Basic Instrument Data slides for breakout)
Data Downlink	Study output (see Astro2020_RFI2.pdf for suggested values)
Data Storage	Study output; must be sufficient for spacecraft operations and effective handling of science data downlink, to include 2 days of accumulated science data. (See Astro2020_RFI2 for suggested values.)
Data Latency	NTE 48 hrs (required); daily (goal)
Uninterrupted Observation Time	3000* minutes (9000 minutes, or 6.25 days)

* Time reduced from original value of 4500s to enable GN&C system to meet requirement.

Mission and Spacecraft Requirements (2 of 2)

Requirement	Value, Required (Desired)		
Slew Requirements	60 degrees in 180 minutes (90 minutes)		
Roll Requirements	Roll along the telescope line-of-sight +/- 30 degrees in 30 minutes		
Avoidance Angles	Sun avoidance angle: 45 degrees (TBR)		
Pointing	3-axis stabilized (roll defined as rotation about the viewing axis of the telescope)		
	pitch	**yaw**	**roll**
Accuracy (arcsec)	1	1	1
Knowledge (arcsec)	0.5	0.5	0.5
Stability (arcsec/sec)*	0.0016	0.0016	0.0016

*** Active isolation system provides the 1.6 mas stability for the science payload. Spacecraft only has to provide the requested accuracy and knowledge.**

Element	Contingency Margin
Spacecraft subsystems mass	30%
Payload (telescope + instruments) mass	30%
Spacecraft power	30%
Payload power	30%
Delta-V	25%
Cost	35%

Basic Instrument Data

All instruments are assumed to be serviceable / replaceable.

Assume same science instrument suite as ATLAST-8:

- Coronagraph
- IFU UV Spectrometer
- WFOV Imager
- Multi-Object Spectrograph

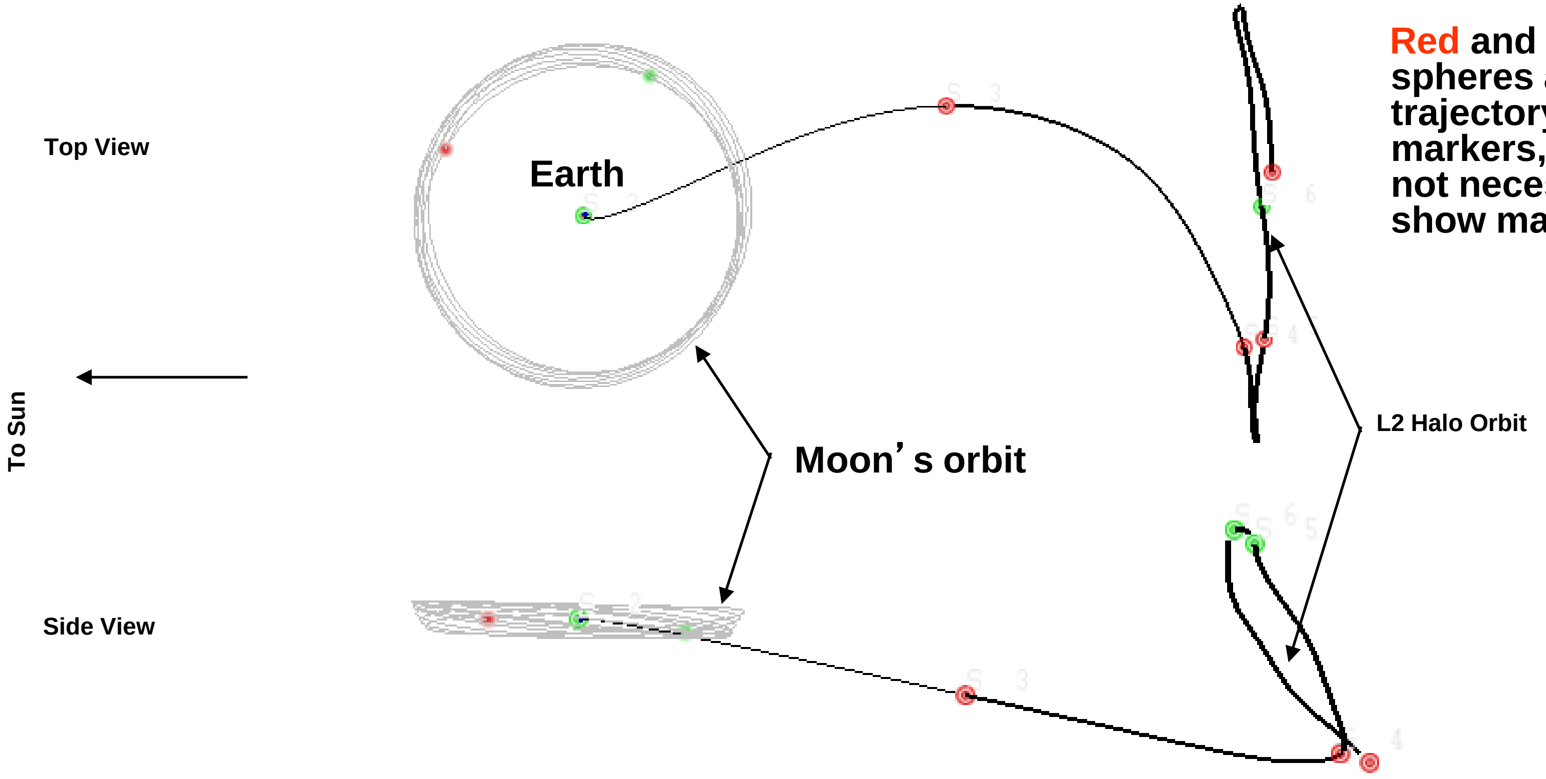
And two facility instruments:

- Fine Guidance Sensor (total of 4 modules)
- Wavefront Sensing and Control System (6 modules)

Ground Rules & Assumptions

Category	Value
Mission	Large observatory in halo orbit similar to JWST at Sun-Earth L2
Launch Year	2035
Mission Duration	30 years
Maximum Time from Launch to Full Capacity	6 months
Servicing Interval	5 years
Servicing Orbit	Earth-Moon L2
Maximum eclipse period	180 minutes (from launch to solar array deployment); no eclipses anticipated thereafter

Operate at SE-L2
Service at EM-L2



Red and **green** **spheres are trajectory segment markers, and do not necessarily show maneuvers.**

Transfer Trajectory from Earth to SE-L2
(figure source: Copernicus mission design and trajectory optimization software)

Halo orbit about Sun-Earth L2 provides stable thermal environment.

Delta-V Budget

	dV		
Manuever	**No Servicing, 30-year mission**	**5 Year Servicing (@EML1/L2)**	**Per Year at SEL2, no servicing**
Launch Correction	52.0 m/s	52.0 m/s	-
Mid-Course Correction	10.0 m/s	10.0 m/s	-
Station Keeping (SEL2)	208.8 m/s	34.8 m/s	7.0 m/s
Station Keeping (EML2, ~6 months)	-	52.8 m/s	-
Momentum Unloading	35.4 m/s	5.9 m/s	1.2 m/s
Transfer from SE L2	-	50.0 m/s	-
Transfer to SE L2	-	50.0 m/s	-
Margin	-6.2 m/s	44.5 m/s	
Margin (%)	-2%	15%	
Total	**300.0 m/s**	**300.0 m/s**	**8.14 m/s**

Using margin, can continue at SE-L2 for more than 5 years without refueling.

MASS BUDGET

LUVOIR (Large Ultra-Violet / Optical / Infra-Red) Telescope

“AMATEURS THINK ABOUT TACTICS, PROFESSIONALS THINK ABOUT LOGISTICS”

GENERAL ROBERT H. BARROW, USMC
(COMMANDANT OF THE MARINE CORPS)

Logistics for Space Telescopes are:

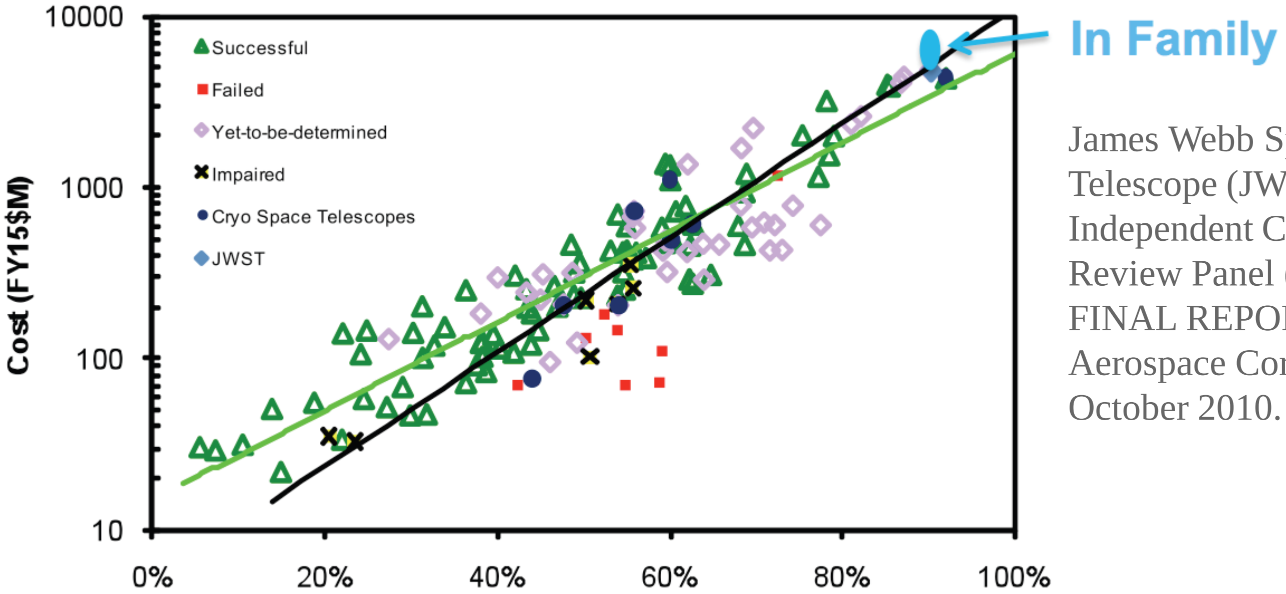
- **Launch Vehicle Payload Mass Capacity**
- **Launch Vehicle Payload Volume Capacity**
- **Budget Amount and Phasing**

Complexity Drives Cost

Design complexity required to package a large mission concept into a small launch vehicle imposed mass and volume constraint drives cost.

The mass and volume capacities offered by the SLS enable simpler designs with higher design allowable mass margins.

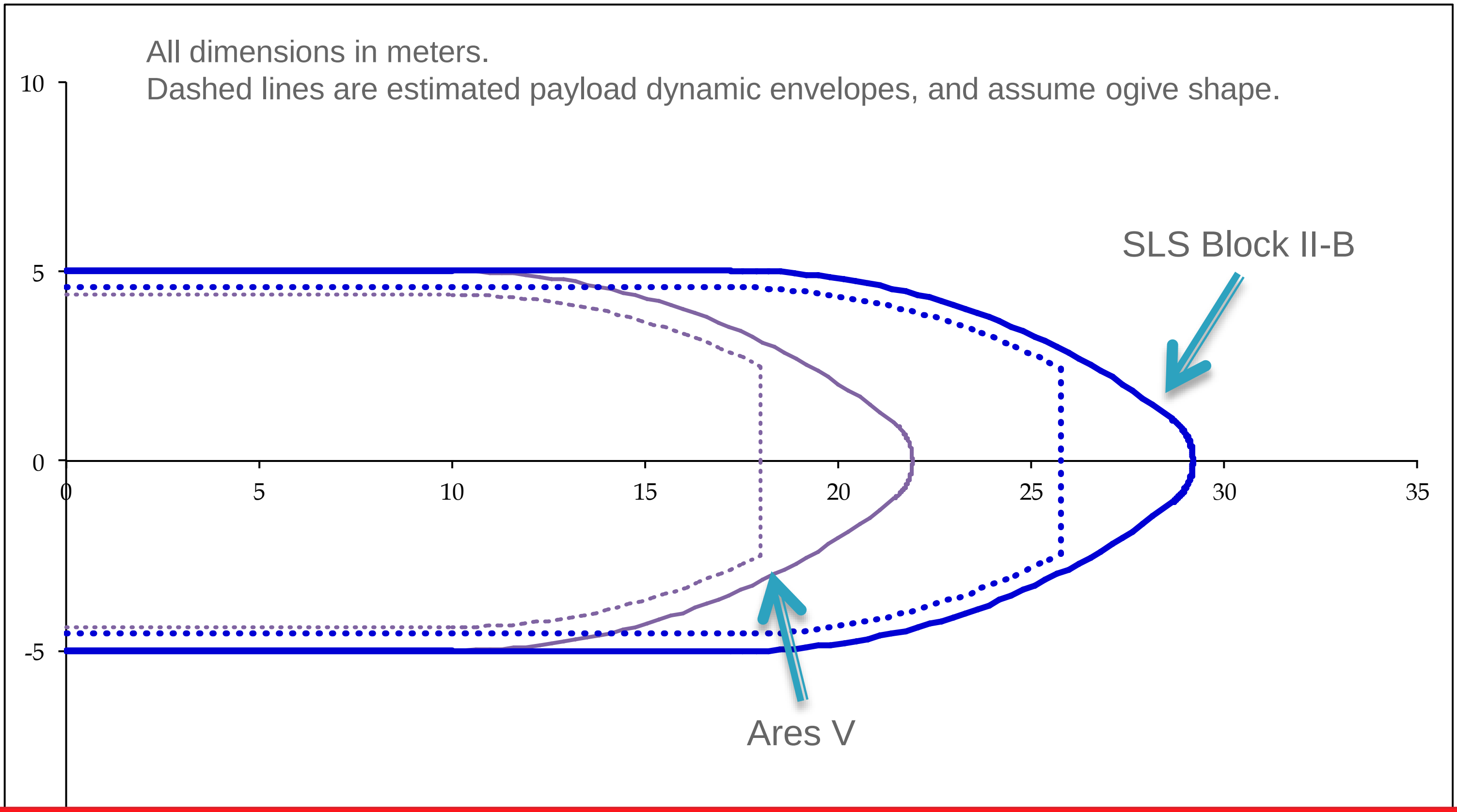
Higher mass margins allows use of standard engineering design practices and reduces ground handling risk.



James Webb Space Telescope (JWST) Independent Comprehensive Review Panel (ICRP) FINAL REPORT, The Aerospace Corporation, 29 October 2010.

SLS Block II-B Capacity

Volume	C3	Payload Mass (kg)
10 m x 26 m	-0.7 km2/s2 (SE-L2 transfer)	46,300



C3=-0.7 km2/s2 is the energy required to put a payload mass into a SE-L2 transfer trajectory

Compared to Ares V, payload volume is same diameter but much longer, so secondary mirror can be fixed rather than deployable.

Mass Allocation for Mission

Mission Concept is Mass Constrained to 32 mt.

Mass Margins	Payload Capability (kg)
0 %	46,300
-15 % Launch Vehicle Margin	40,260
-30% Payload Mass Reserve	32,046

This Mass budget is allocated between systems/sub-systems:

- Telescope Assembly
- Science Instruments
- Spacecraft
- Propellant

Using ATLAST-8 as starting point, new subsystem designs were developed and detailed analysis was performed.

Multiple iterations were required to close the design.

Mass Allocation for Design

-	Ares V ATLAST	SLS ATLAST
	mass [kg]	mass [kg]
TOTAL OBSERVATORY MASS	**50,449**	**32,085**
Optical Tube Enclosure (OTE)	38,417	21,433
Primary mirror assembly	29,800	12,513
Primary mirror	22000	9547
Primary mirror support truss	4000	2728
Primary mirror flexures	-	6
Launch lock mechanisms	3500	132
Primary mirror central baffle	300	100
Secondary mirror assembly	1,050	637
Aft Optics	2,167	1,481
Structure	5,400	5,350
Active Thermal Control	-	1,452
Science Instruments	1,789	1,789
Spacecraft Bus	4,577	4,197
Attitude Control System	312	499
Command And Data Handling (C&DH)	120	140
Instrumentation and Monitoring	212	0
Communications	114	114
Power Subsystems	1104	1,104
Thermal Management System	974	554
Structures	1300	1,345
Propulsion	401	401
Docking	40	40
Propellant allocation	5,666	4,666

Used ATLAST-8 mass for all Systems & Sub-Systems except Primary Mirror and its Support Structure.

ATLAST-8 PMA mass budget was ~30 mt with 0% margin.

ATLAST-12 PMA mass budget is ~12.5 mt with 30% margin.

Primary Mirror Assembly Mass & Diameter

Assuming:

- Maximum Mass of 12,500 kg for the Primary Mirror Assembly,
- Areal Density of between 75 and 150 kg/m2 for the PMA

PMA Maximum Mass Allocation (kg)	Areal Density (kg/m2)	Primary Mirror Diameter (meters)
12,500	75	14.5
12,500	**100**	**12.6**
12,500	150	10.3
12,500	250	8.0

Note: preliminary analysis indicates the PM structure needs ~4,000 kg, not to survive launch, but to be mechanically stable on-orbit. This leaves ~8,500 kg for the PM mirror or ~65 kg/m2 for a 13-m substrate.

(This is the areal density being demonstrated on AMTD.)

Two Key Points

1) Mass budget for the primary mirror assembly (and for the telescope) is independent of architecture (monolithic versus segmented, segmentation style, on- versus off-axis, etc.)

2) Mass budget enables the use of currently available low-cost ground mirror technology. Future technology development will only reduce cost, risk and mass of these technological solutions.

TMT 1.44-m Mirror Segment

- Areal Density of 150 kg/m2
- Areal Cost of ~$0.3M/m2

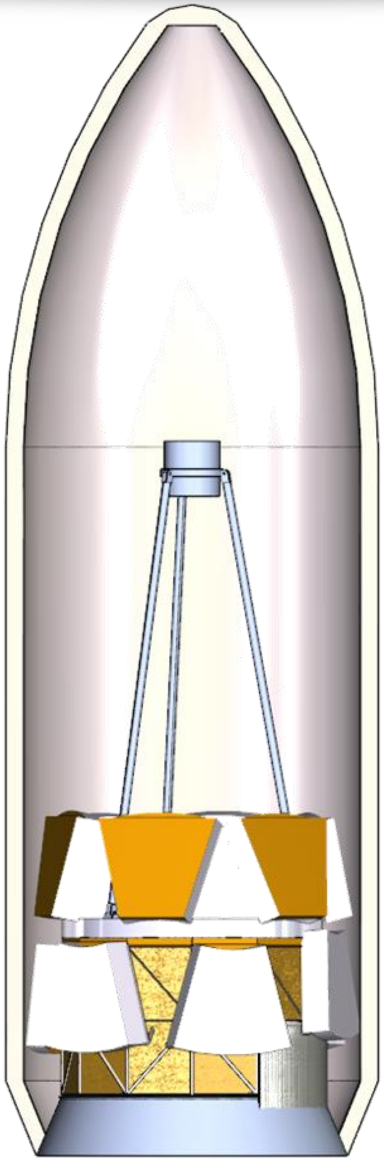
Arizona 8.4-m Mirror

- Areal Density < 300 kg/m2
- Areal Cost of < $0.5M/m2

OBSERVATORY CONFIGURATION

LUVOIR (Large Ultra-Violet / Optical / Infra-Red) Telescope

Telescope Stowed Configuration



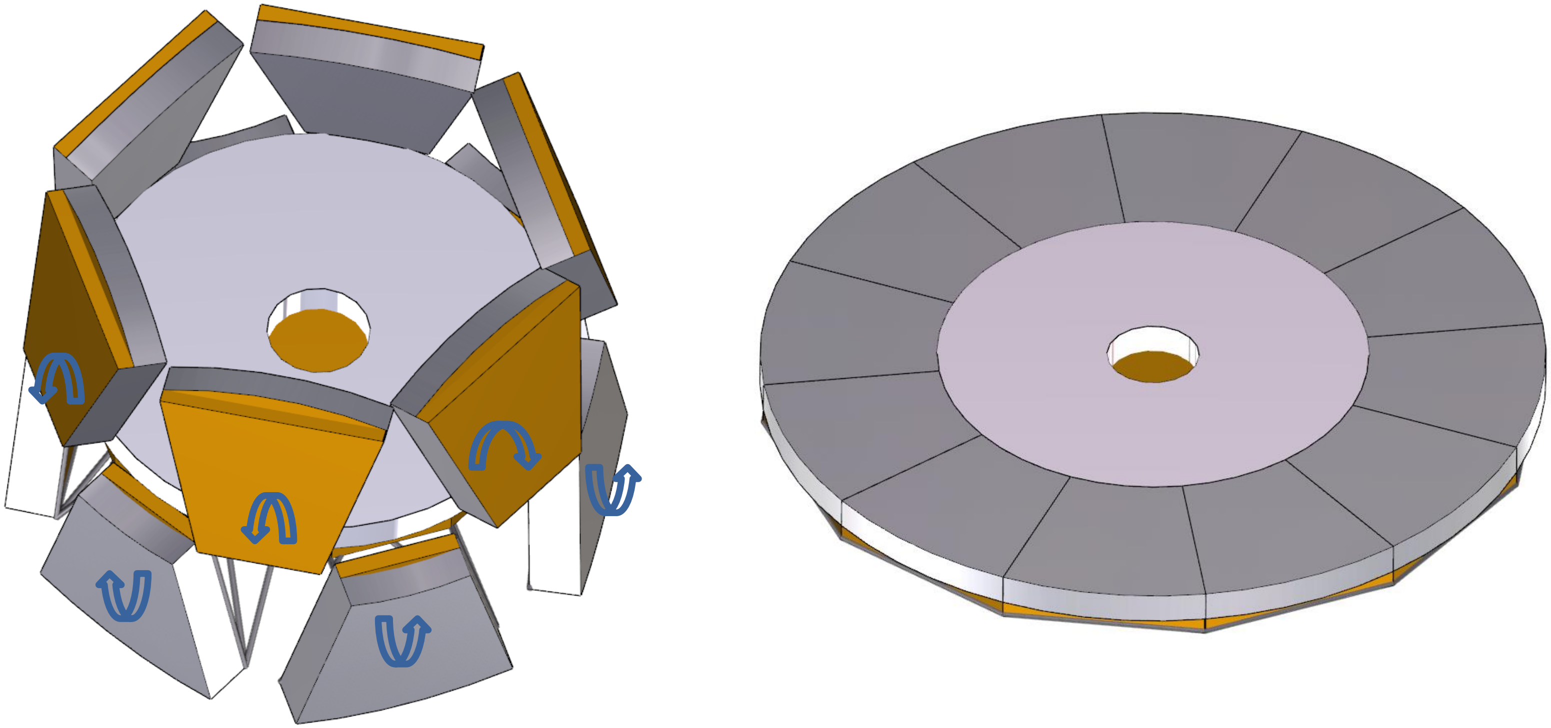
Design team examined two configurations:

- Fold-Forward / Fold-Aft
- Drop Leaf (JWST)

Design Team was asked to find a configuration that folded all Segments down to allow space above the Primary Mirror for the Sun Shade.

But, given the short duration of the study, that design was not fully explored.

PM Stow/Deploy Configuration



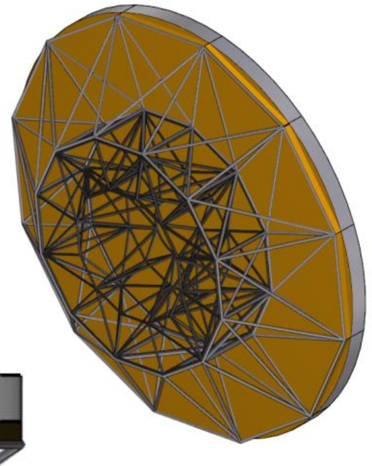
Alternate configurations might provide better packaging, including:

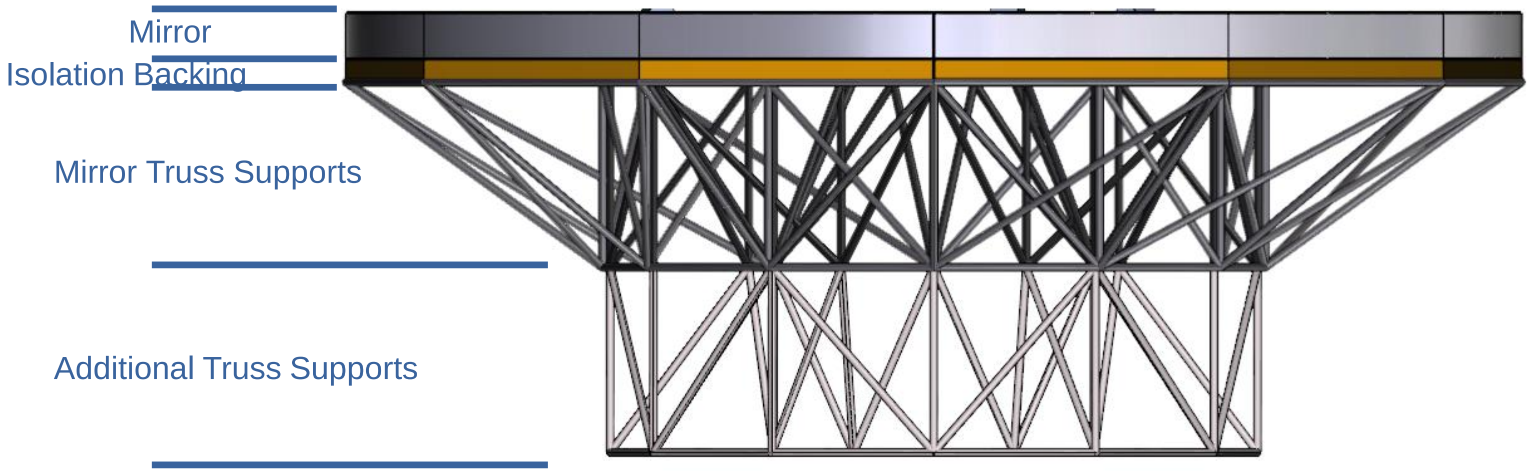
- Larger Petals (or ‘rafts) without a Center Segment.
- JWST Style Drop Leaf

PMA Configuration

PMA Design Constraints:

- Minimum strength requirement (NASA-STD-5001A)
- SLS applied launch load conditions.
- First natural frequency > 20 Hz
- Ultimate Factor of Safety = 1.4





Analysis and Assumptions

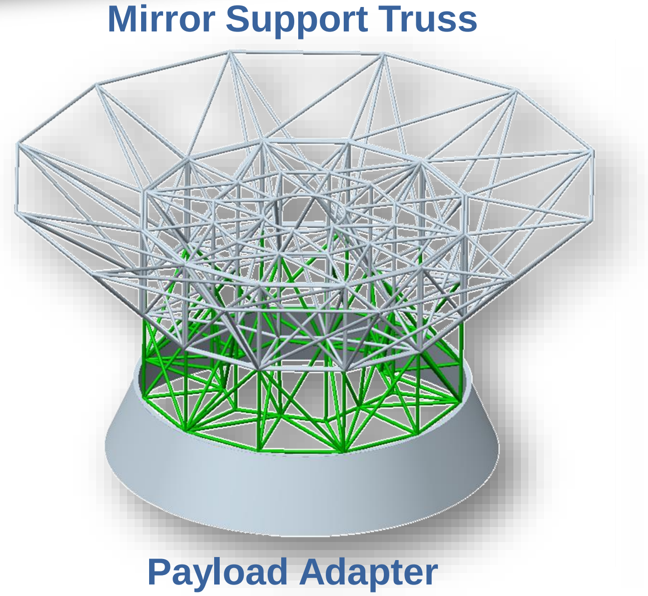
Finite Element Models developed and Structural Analysis performed to obtain mass estimates for:

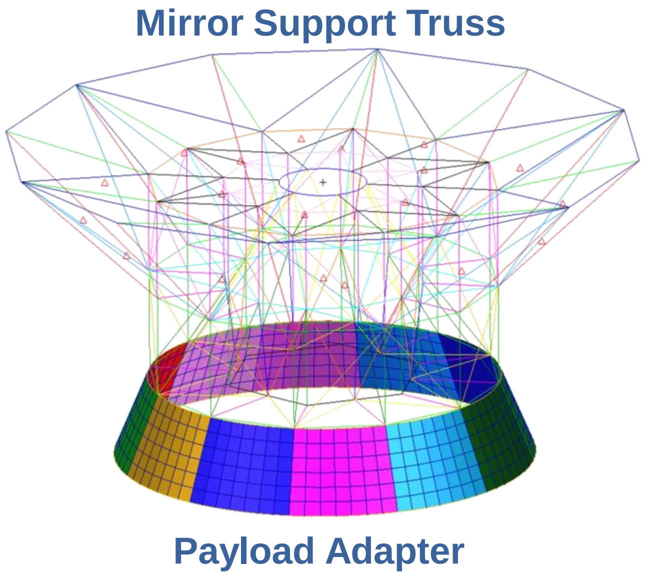
- Mirror Support Structure
- Payload Adapter

Structural optimization accounts for strength, global stability, and natural frequency requirements

Truss Structure uses Composite Tubes

Payload Adapter uses honeycomb composite face sheet sandwich construction





Ascent Loads and Constraints

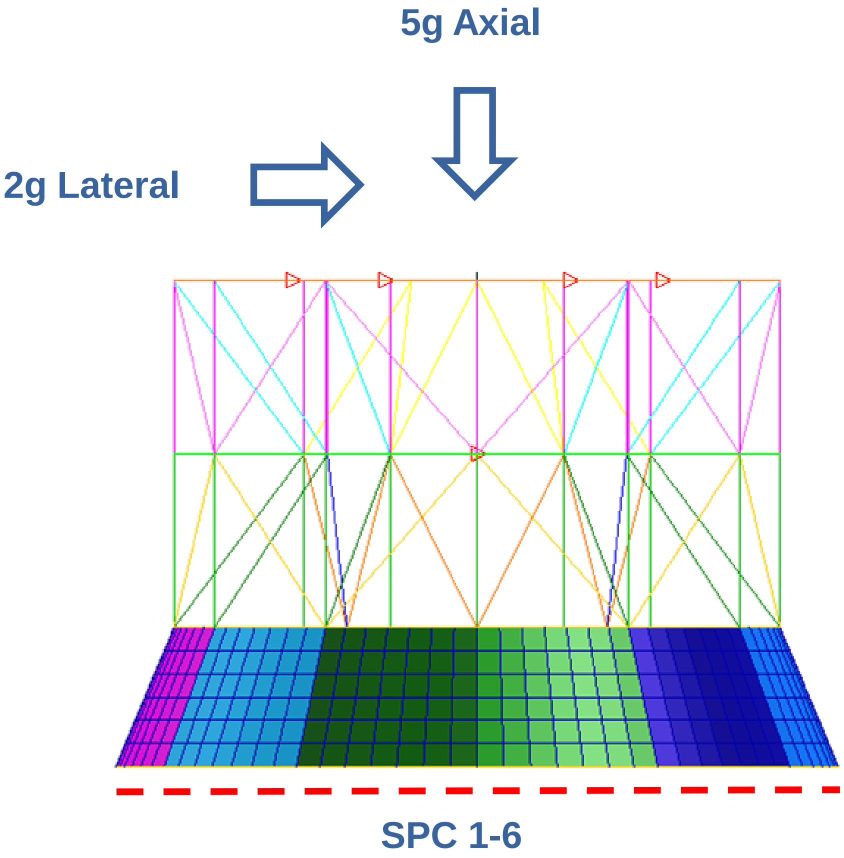
Model loads are applied using model mass and inertial acceleration

Critical load condition assumed to be SLS Ascent

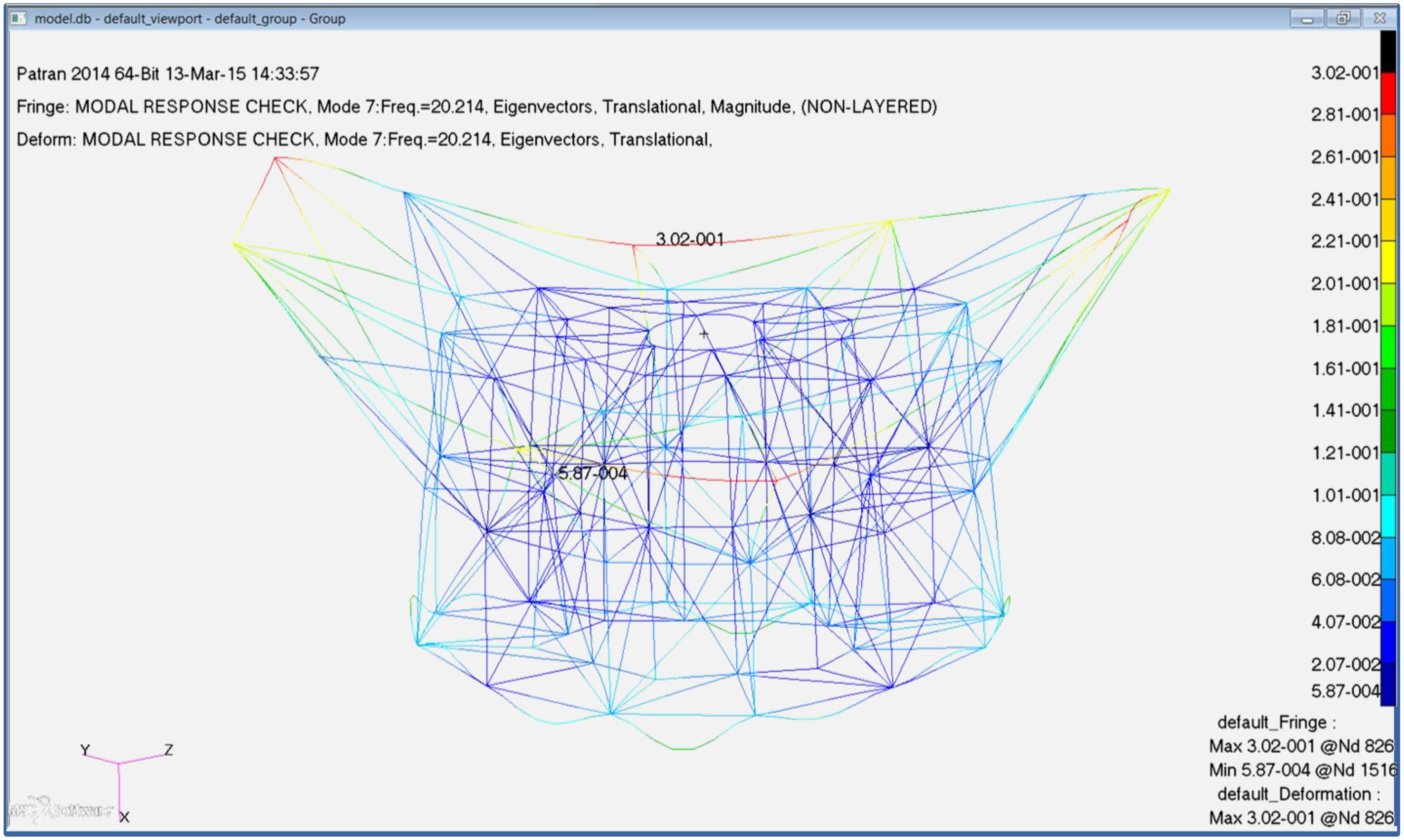
- Case 1 : $5g_x$, $2g_y$
- Case 2 : $5g_x$, $1.414g_y$, $1.414g_z$

Assembly constrained at the aft end of the payload adapter

Mirror petal mass distributed around periphery of central mirror truss.



Truss Structure
Natural Frequency



model.db - default_viewport - default_group - Group

```
Patran 2014 64-Bit 13-Mar-15 14:33:57
Fringe: MODAL RESPONSE CHECK, Mode 7:Freq.=20.214, Eigenvectors, Translational, Magnitude, (NON-LAYERED)
Deform: MODAL RESPONSE CHECK, Mode 7:Freq.=20.214, Eigenvectors, Translational,
```

```
default_Fringe :
Max 3.02-001 @Nd 826
Min 5.87-004 @Nd 1516
default_Deformation :
Max 3.02-001 @Nd 826
```

Deployed 1st Natural Frequency (20.2 Hz)

Wavefront Stability - Mechanical

Mechanical disturbances

from spacecraft such as reaction wheels or mechanisms, or
from the solar wind

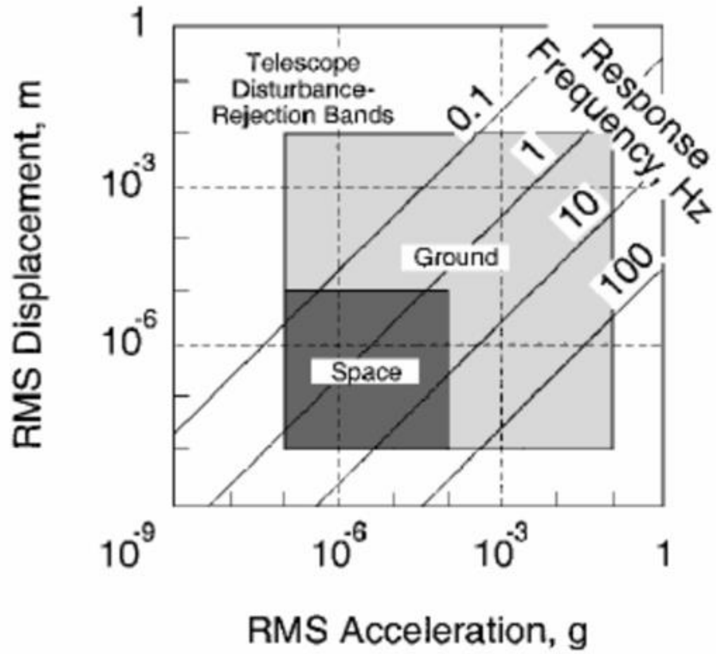
can excite modal vibration modes.

Per Lake, rms wavefront error is proportional to rms magnitude of the applied inertial acceleration (a_{rms}) divided by square of the structure's first mode frequency (f_0)

$$WFE_{rms} \sim a_{rms}/f_0^2$$

To achieve < 10 pm rms requires

First Mode Frequency	RMS Acceleration
10 HZ	< 10^-9 g
100 HZ	< 10^-7 g



Lake, Peterson and Levine, "Rationale for defining Structural Requirements for Large Space Telescopes", AIAA Journal of Spacecraft and Rockets, Vol. 39, No. 5, 2002.

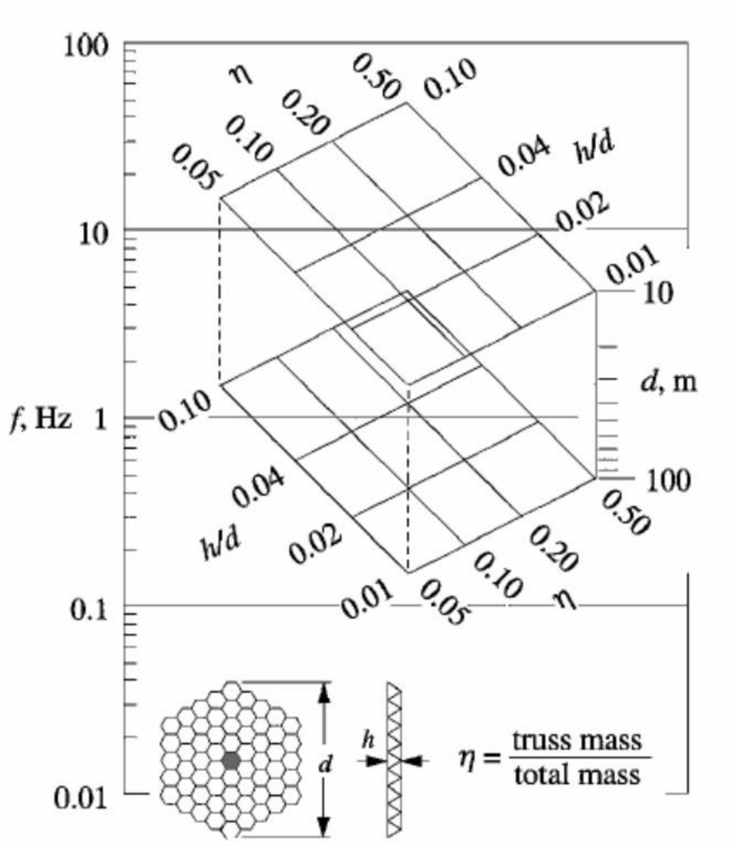
Wavefront Stability - Mechanical

One way to gain mechanical wavefront stability is to make the system stiffer. A 2X increase has a 4X benefit.

For a Truss Mirror support

where Truss Mass = PM Substrate Mass.

Diameter	Depth	f_0
10 m	0.2 m	10 Hz
10 m	2.0 m	100 Hz
20 m	0.4 m	10 Hz
20 m	4.0 m	100 Hz



Note: Adding Stiffness requires MASS.

Another way is to increase isolation.

A final way is active control.

Lake, Peterson and Levine, “Rationale for defining Structural Requirements for Large Space Telescopes”, AIAA Journal of Spacecraft and Rockets, Vol. 39, No. 5, 2002.

Structure Conclusions

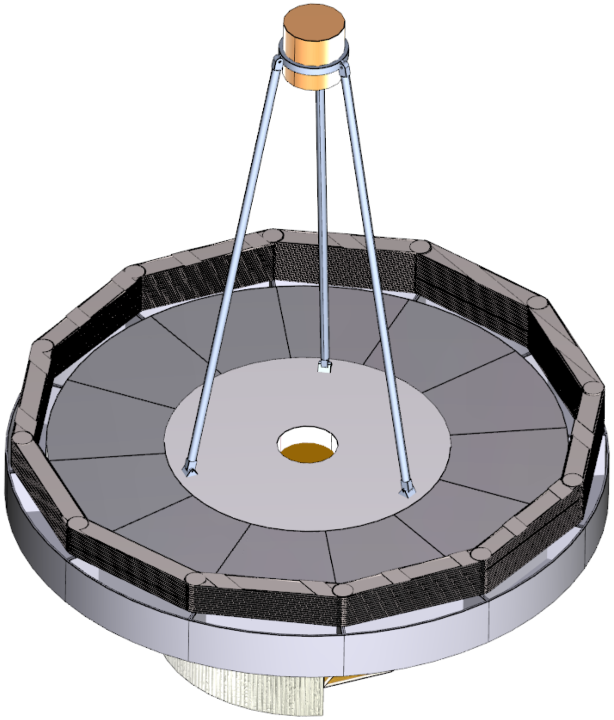
Structure mass is driven by the 20Hz 1st mode frequency requirement during operation

Component	Qty	Unit Mass (kg)	Total Mass (kg)	Contingency	Predicted Mass (kg)
Mirror / BUS Truss Structure	1	4036	4036	30%	5246
Payload Adapter	1	320	320	30%	416
Total			**4356**	**30%**	**5662**

An in depth dynamic analysis including the effects of active and passive isolation systems is required to accurately estimate PMA structure mass

- Frequency response of the mirror support truss structure is highly dependent on the type of isolation / damping that exists at the mirror / truss attach points
- Structural mass could be significantly reduced by taking into consideration the mirror and BUS isolation systems

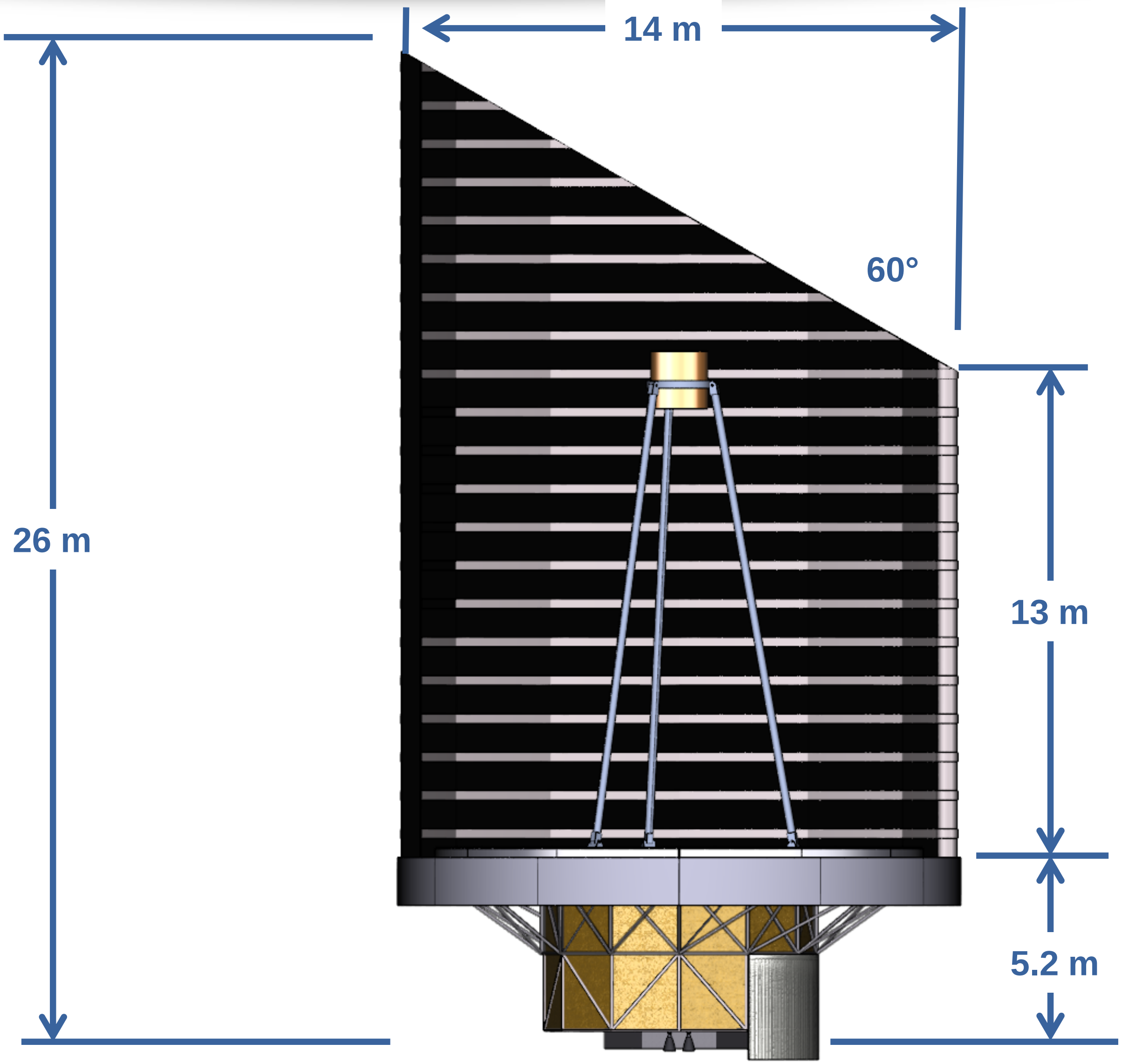
Baffle Tube Configuration



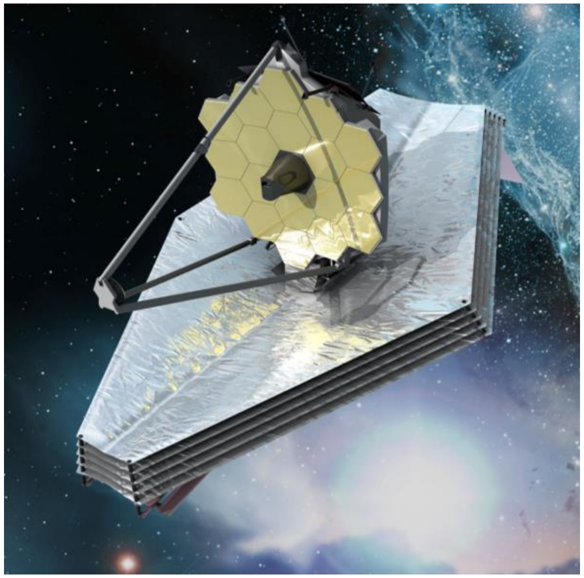
Tube Stowed

Tube Deployed

Baffle Tube Configuration

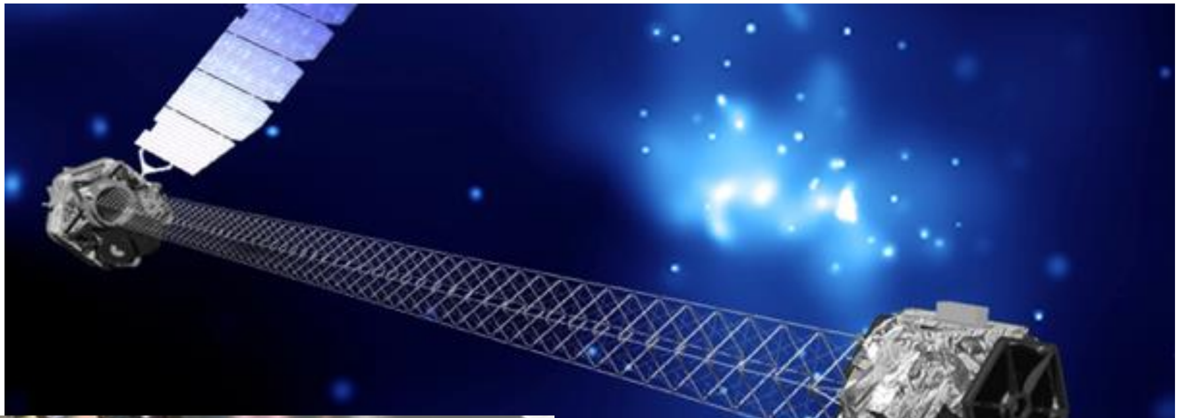


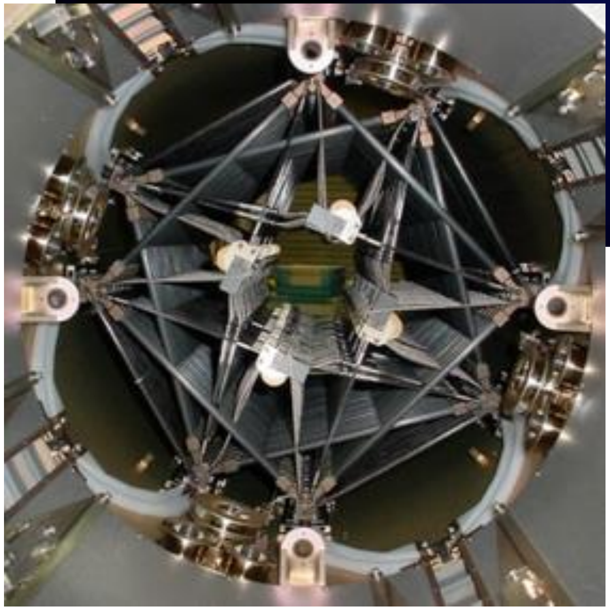
External flat JWST style sunshade may offer packaging and thermal advantages. But, GSFC is studying it, so we did not.



Baffle Tube Deployment

- Deployment booms and mechanisms mass estimated from NuSTAR deployable booms





NuSTAR booms built by ATK Goleta. Their deployable structures have flown on ISS, Mars landers, and a much larger but similar mast on STS Endeavor in 2000.

Length: 10 meters
Mass: 30 kg
Motor: 2.5 kg per boom

LUVOIR has 12 sided mirror; need 2 booms per side, and 12 around bottom of mirror = 36.

Add some extra length for the scarfed sunshade:

Total of 40 booms and 40 motors.

This is just a placeholder. More detailed analysis needs to be done.

Alternative Concept

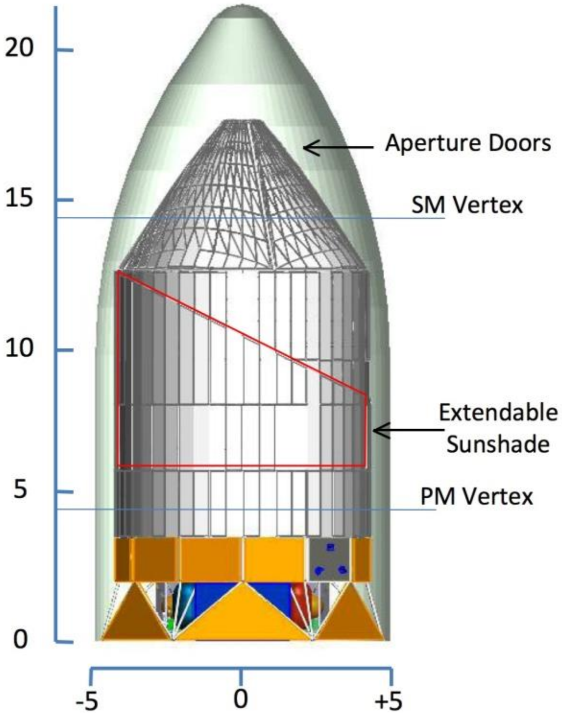
Drop-Leaf Configuration

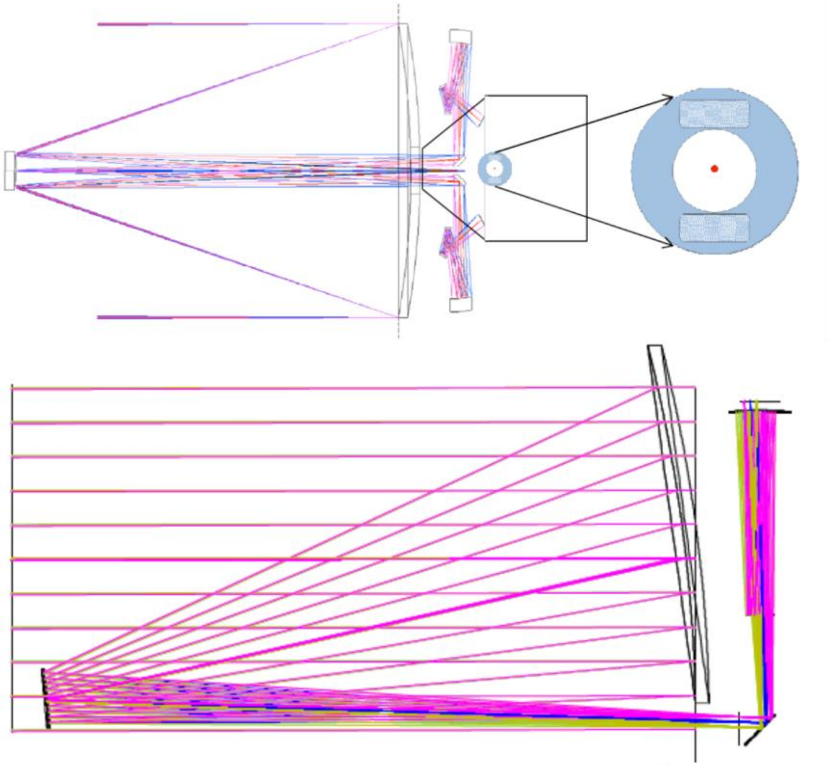
Drop-Leaf Configuration

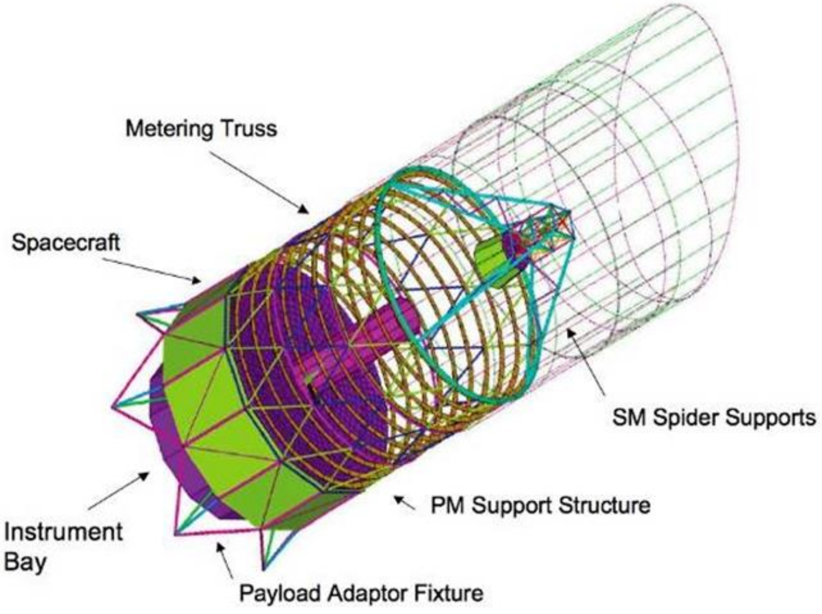
Drop-Leaf may be more compatible with a deployed tube Sunshade.

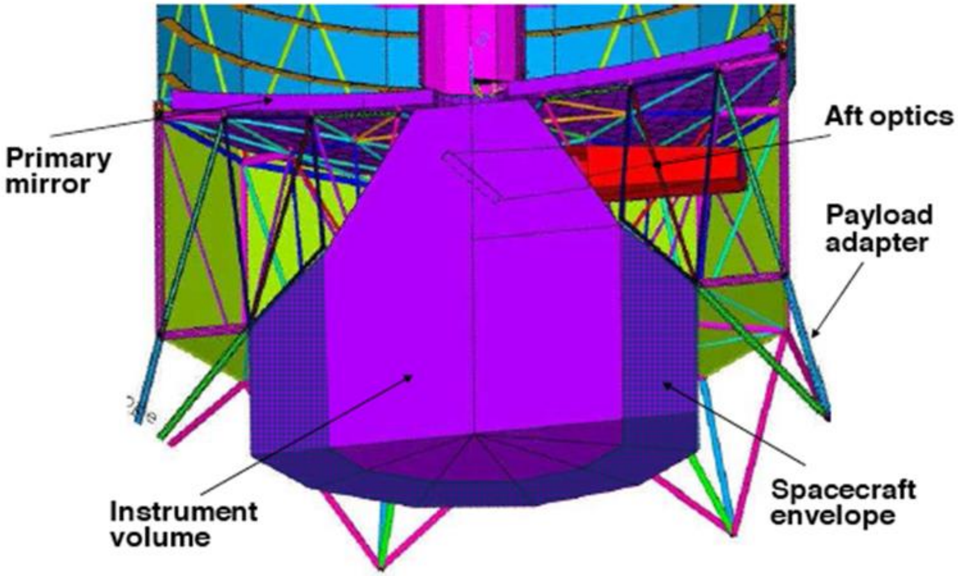
ATLAST-8 from 2007 ATLAST STUDY
and
Northrop Grumman Concepts

ATLAST-8m

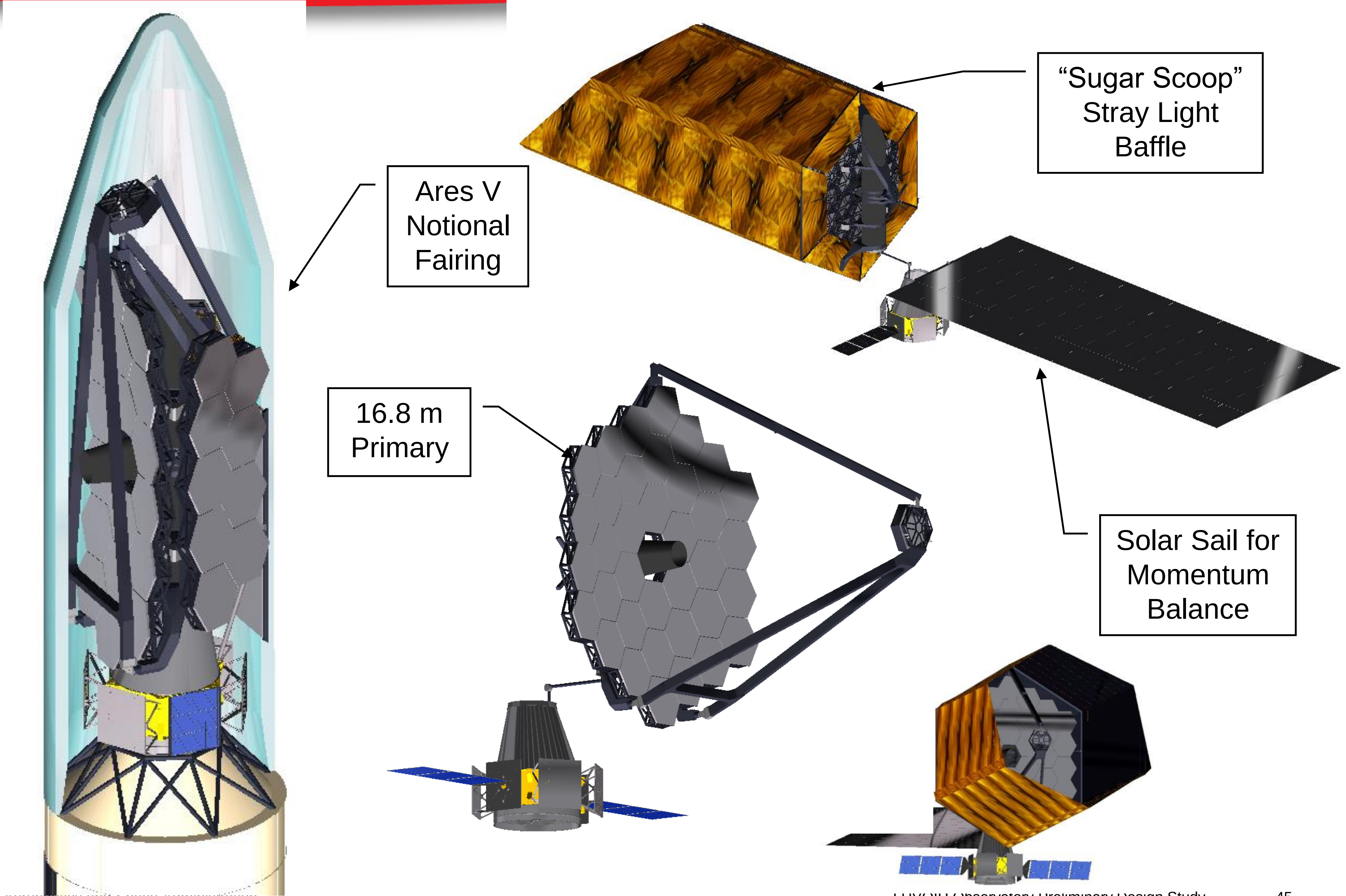

20
15
10
5
0
-5
0
+5
Aperture Doors
SM Vertex
Extendable Sunshade
PM Vertex




Metering Truss
Spacecraft
SM Spider Supports
PM Support Structure
Instrument Bay
Payload Adaptor Fixture


Primary mirror
Aft optics
Payload adapter
Instrument volume
Spacecraft envelope

16.8 m “Chord-Fold” Deployment Concept



Ares V Notional Fairing

“Sugar Scoop” Stray Light Baffle

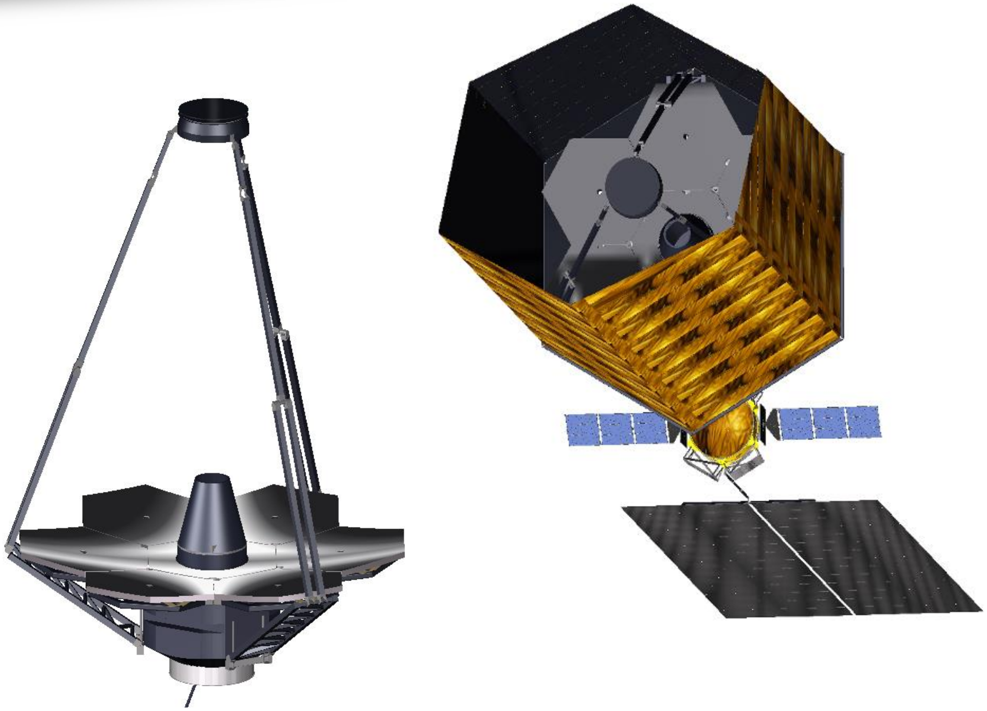
16.8 m Primary

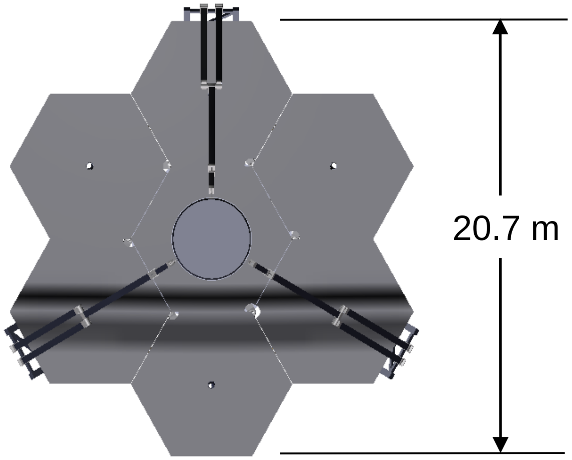
Solar Sail for Momentum Balance

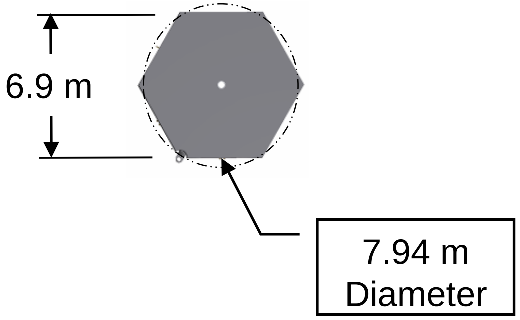
21 Meter Stacked Hex Deployment Concept

Ares V “Notional Fairing”

Seven 8-m pt-pt Hexagonal Mirror Segments

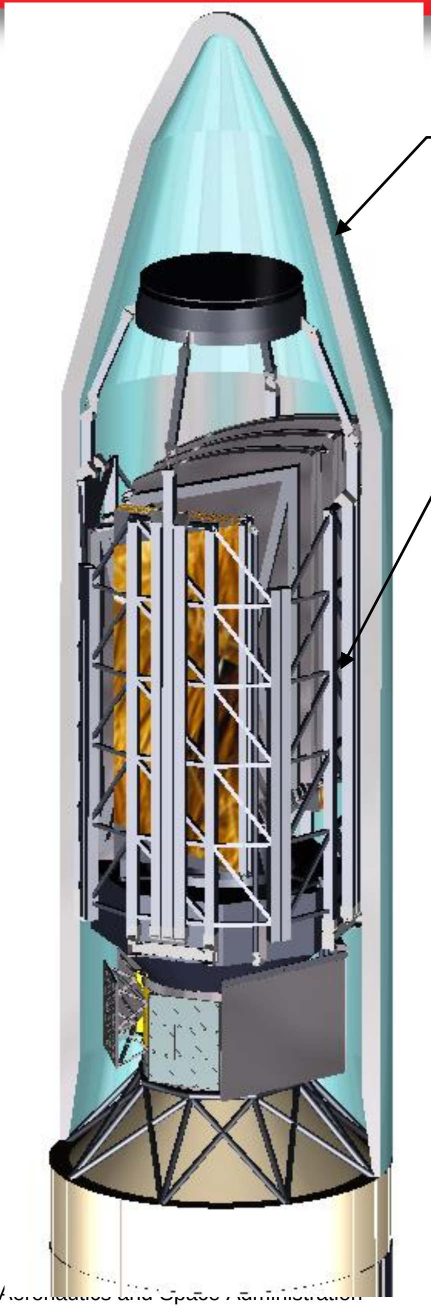






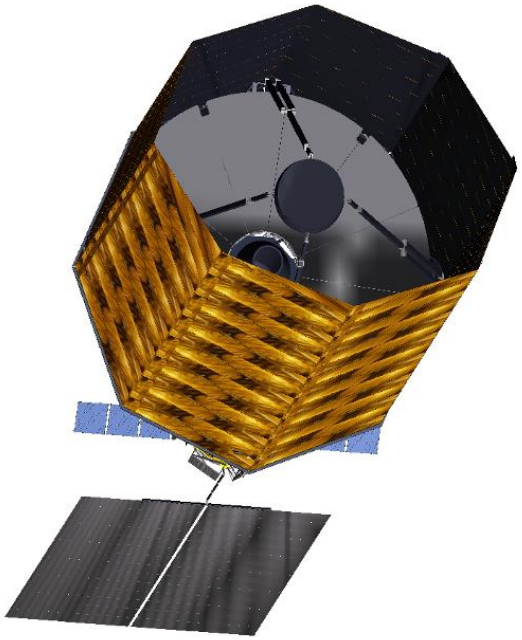
Single Mirror Size

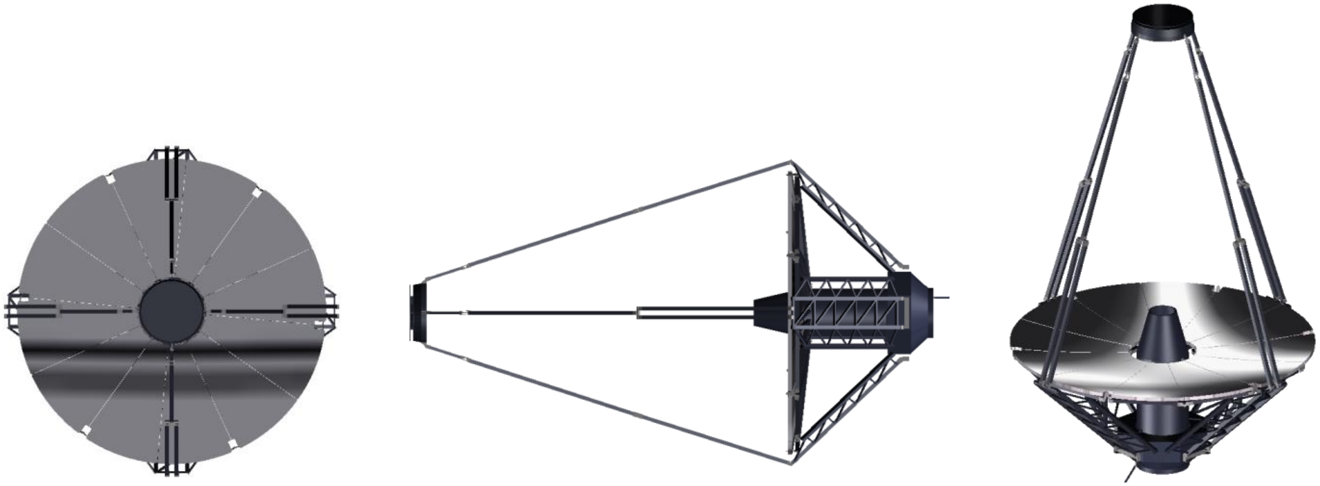
24 Meter Fan-Fold Deployment Concept



Ares V
“Notional
Fairing”

12 Pie-Shaped
Mirror Segments





THERMAL

Thermal Control

Tube has sufficient insulation for telescope to passively reach 200K for infrared observations.

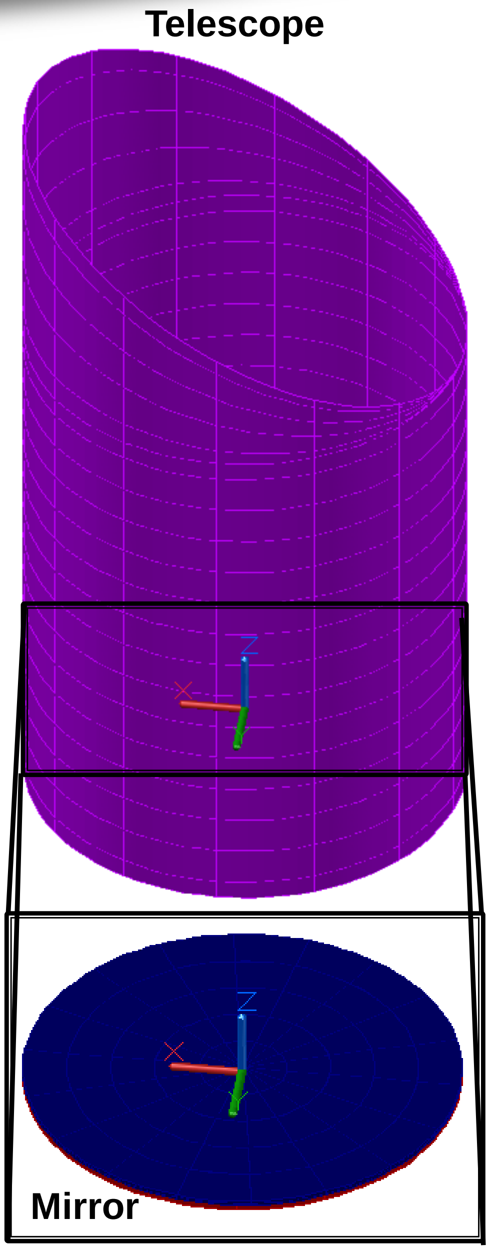
- Provides insulation mass.

Heaters in lower Tube and around Primary Mirror heat Primary Mirror front surface to above 0C to prevent ice or frost.

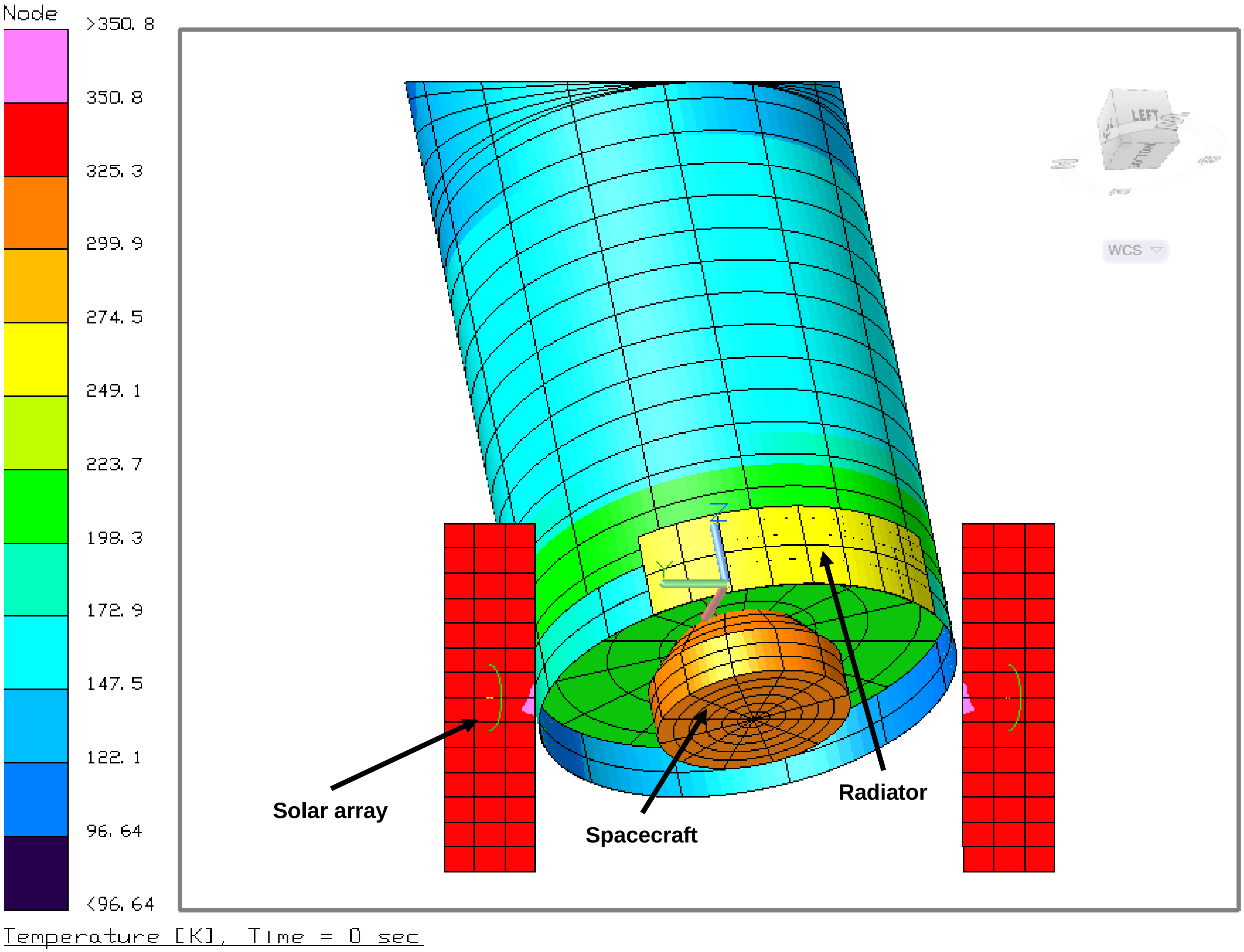
- Provides electrical power and heater mass.

MLI effective emissivity was used to determine MLI areal density.

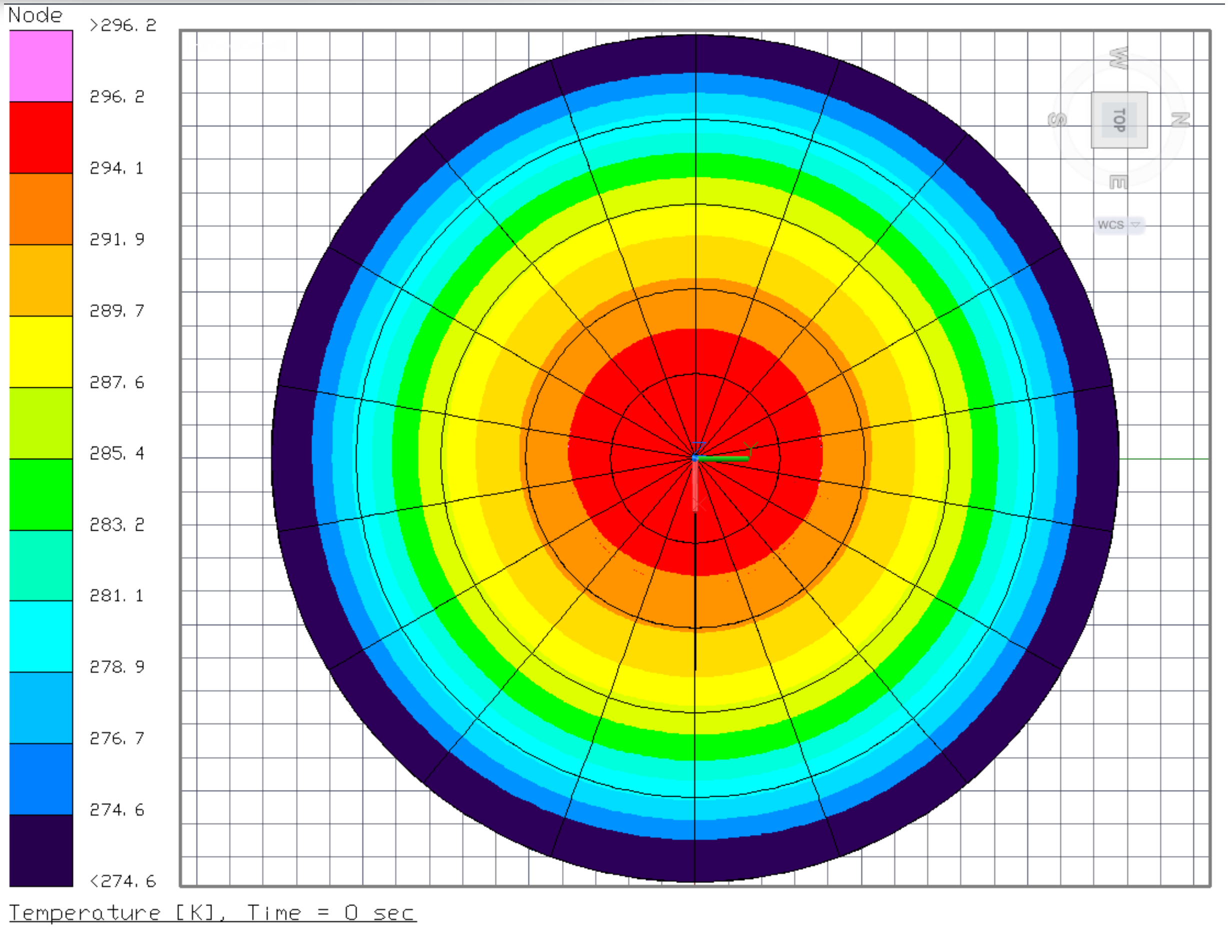
Heater blanket is assumed to have the same areal density as the MLI.



Spacecraft/telescope Thermal Model



Telescope Thermal Control Results



Mirror Temperature

20K radial thermal gradient can be reduced by using Zonal Heaters.

Thermal Control Sizing Results

Component	Qty	Unit Mass (kg)	Total Mass (kg)	Power (W)	Margin	Pred. Mass (kg)	Pred. Power (W)
MLI	1	565[1]	565[1]	-	30%	734.5	-
Heater Blanket	1	130[2]	130[2]	-	30%	169	-
Heaters	-	1560[3]	1560[3]	3800[4]	30%	2028	4940

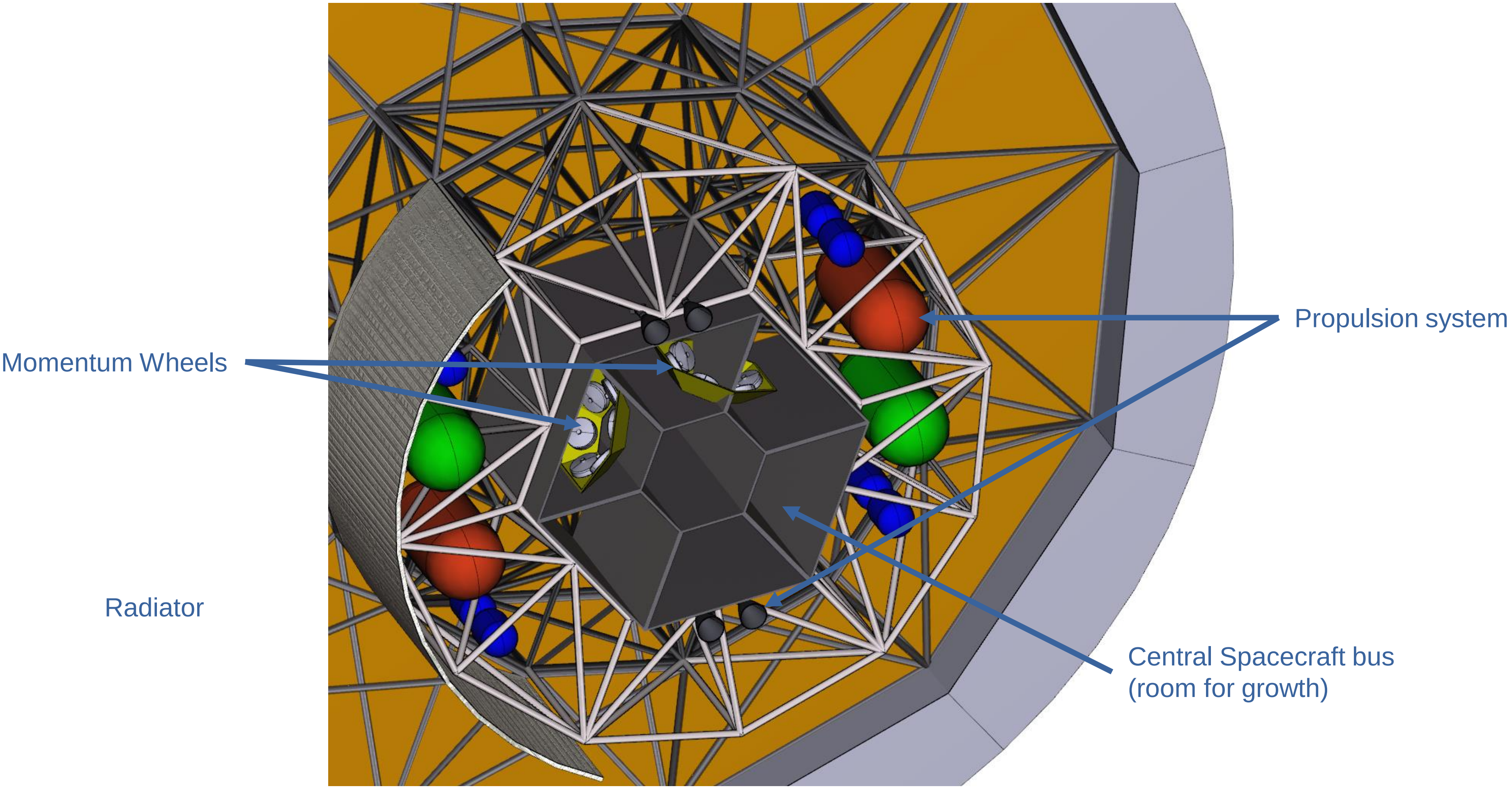
1. MLI mass was determined by: first the number of layers in the MLI was estimated from the effective emissivity, then the areal density of the MLI was determined, and finally the area covered in MLI was multiplied by the above areal density.

2. Heater blanket mass was determined by taking the MLI areal density and multiplying it by the heater blanket area.

3. Heater mass was determined by multiplying the heater surface area by 2 kg/m^2 as suggested in AIAA’s “Element’s of Spacecraft Design” edited by Charles D. Brown.

4. Heater power was determined by modelling in Thermal Desktop.

Spacecraft Configuration



Propulsion system

Momentum Wheels

Radiator

Central Spacecraft bus
(room for growth)

Spacecraft Details

The Advanced Concept Office performed specific designs including mass and power budgets for the following Spacecraft Sub-Systems:

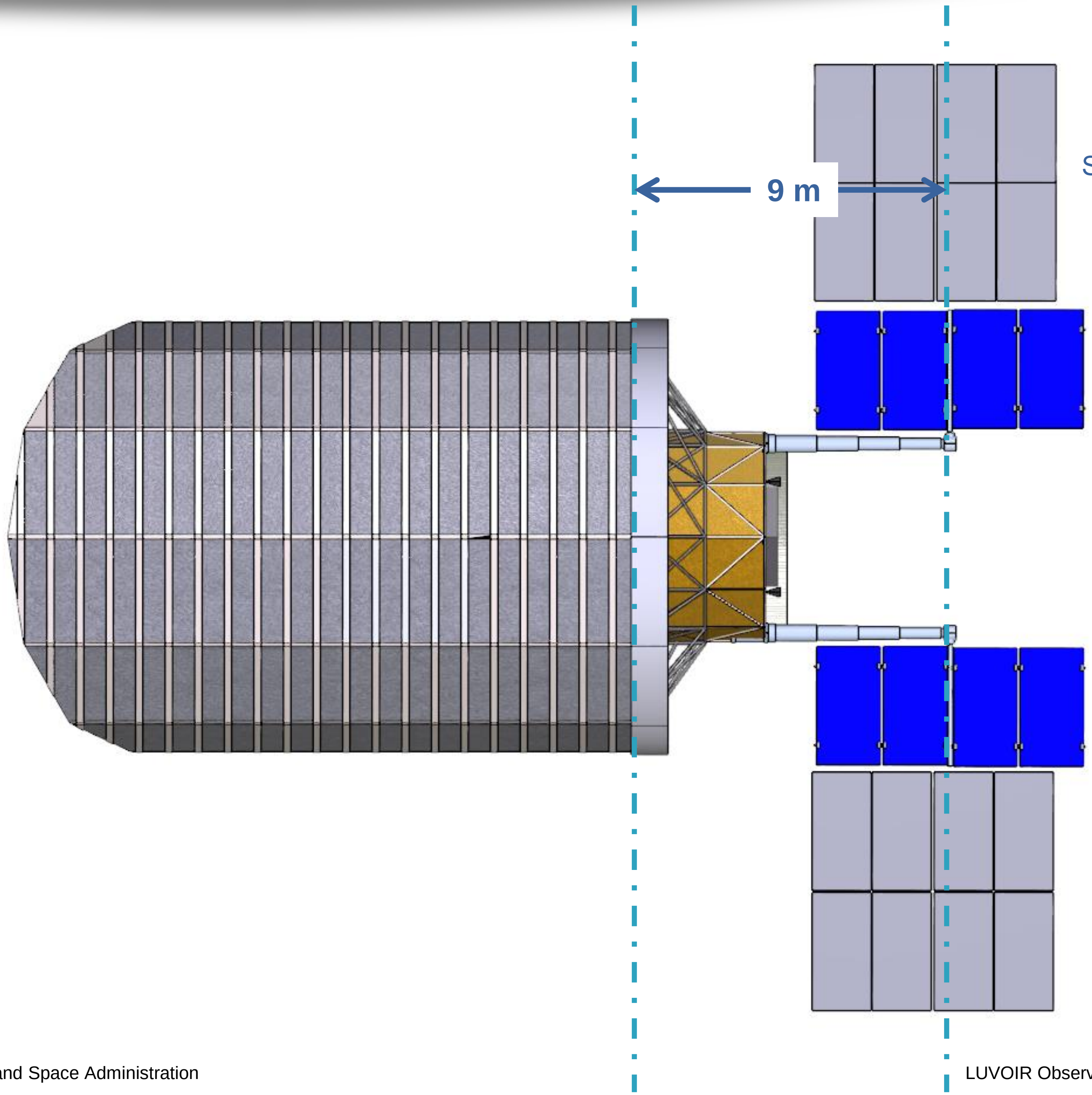
- Propulsion
- Guidance Navigation and Communication
- Command and Data Handling
- Communication
- Thermal Control
- Power System (need 13kW including 30% margin)
- Docking / Servicing

OPERATIONS

Ground Rules and Assumptions

Category	Value
Uninterrupted Observation Time	3000 min
Fast Slew Requirements	60 degrees in 180 minutes
Pointing Control	1 arcsec
Pointing Accuracy Knowledge Stability (Jitter)	3-axis stabilized 1 arcsec 0.5 arcsec 0.0016 arcsec/sec

Long Observation: Solar Panels & Kites balance Solar Torque



Model Approach

Inertia Model

	Mass (kg)	Model	Diameter (m)	Length (m)	*Center of Mass (m)
A: S/C Bus	13,320	Solid cyl	6	2	-3.75
B: Primary Support Structure	9,448	Solid cyl	13	2.75	-1.375
C: Primary Mirror	18,054	Solid cyl	12.7	0.15	0
D: Sunshade	4,612	Hollow cyl	13.2	20	10
E: Secondary Mirror	865	Solid cyl	2	1	15.5
F: Solar Arrays	430	Solid	14	8	-10.9
Total S/C	**46,299**				**-0.174**

*Relative to middle of primary mirror thickness

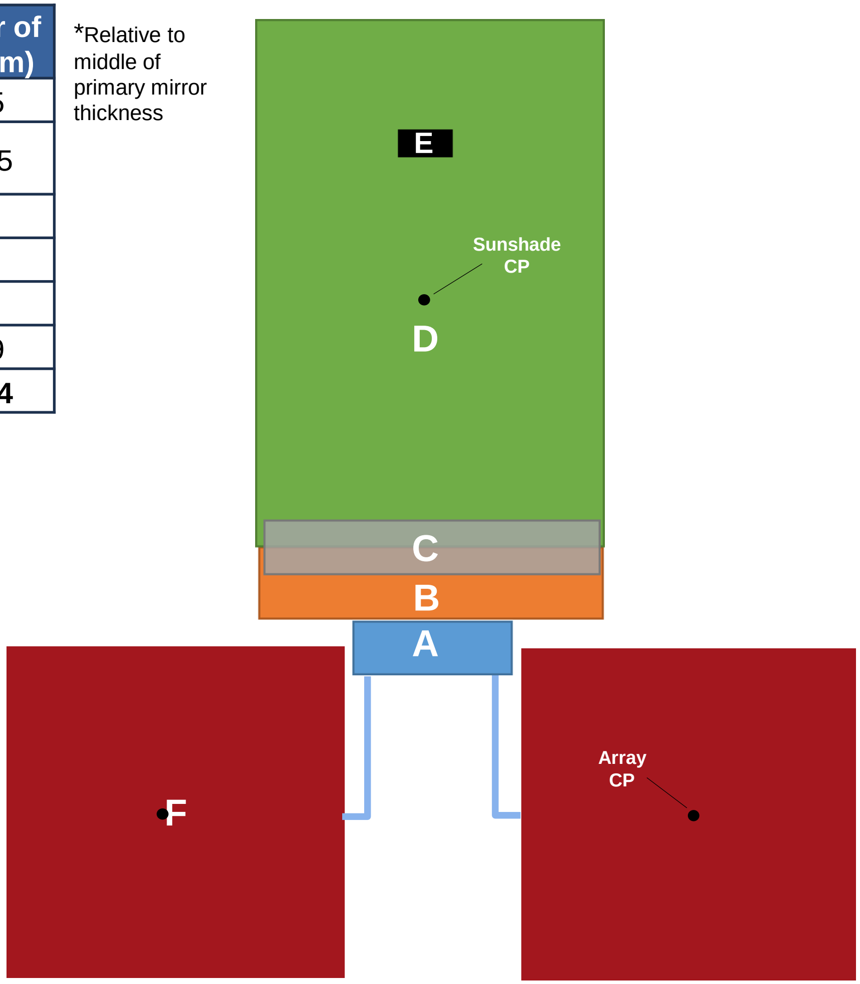
Inertia Estimates *(without arrays)*

	Inertia (kg-m³)
Ixx	1,450,989
Iyy	1,450,989
Izz	824,853

Solar Pressure Model

	Area (m²)	*Center of Pressure (m)	Torque (N-m)
A+B+D (Telescope Body)	311.75	8.166	0.020400
		With 15% Margin:	**0.023455**

*Relative to middle of primary mirror thickness



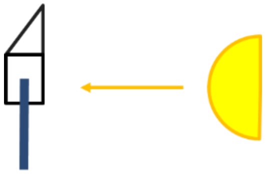
Uninterrupted Observation Window

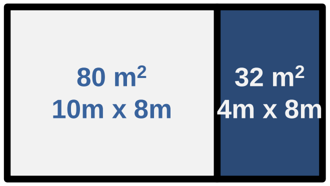
Solar Pressure Model

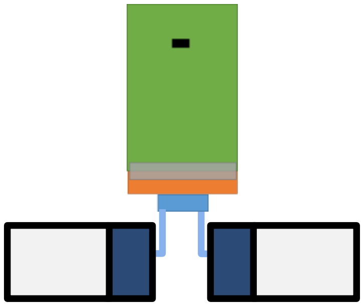
	Area (m^2)	*Center of Pressure (m)	Torque (N-m)	**Momentum Buildup (N-m-s)
Telescope Body (with 15% margin on torque)	311.75	8.166	0.0235	4222
Solar Arrays	64	-10.9	-0.0042	-748.019
Aluminum Mylar "Kites"	160	-10.9	-0.0157	-2833.84
		Net Torque	**$3.555*10^{-3}$**	**640**

*Relative to middle of primary mirror thickness

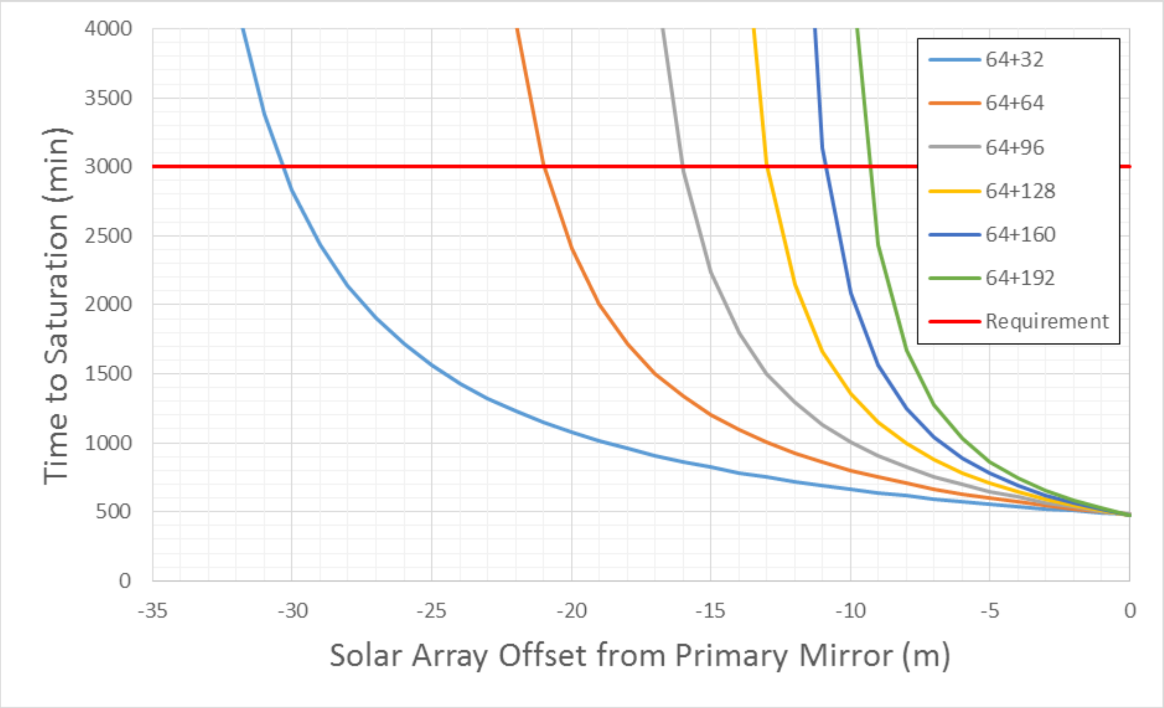
**Over 3000-min observation window. Reaction wheels can store 669 N-m-s of momentum







- Assumptions:
  - 15% margin on telescope body torque
  - Worst-case attitude and orbital position for observation window
    - Normal to sun vector, 0 solar incidence angle
    - At perihelion, solar constant at S-E L2 = 1384 W/m^2
  - Material reflectance
    - 70% reflectance for telescope body
    - 30% reflectance for solar arrays
    - 97% reflectance for aluminum mylar
  - 12 100 N-m-s reaction wheels in 2 hexagonal pyramid configurations
    - Can store up to 669 N-m-s of momentum in the pitch and yaw axes
    - With this configuration, the 3000 min uninterrupted observation time can be met



Sensor and Actuator Info

- Sensors
  - IMU: 2x Northrup Grumman NG-SIRU
    - 0.0003 arcsec/sec stability
    - 12 deg/sec rate range
    - >99.7% success rate over 15 years continuous operation
  - Star Tracker: 2x Ball Aerospace HAST
    - 0.18 arcsec
    - >94% success rate over 7 years
- Actuators
  - Reaction Wheel: Rockwell Collins Teldix Reaction Wheels
    - 0.10 N-m, 100 N-m-s each
    - 2 hexagonal pyramids
      - 669 N-m-s momentum storage in pitch and yaw axes
      - 490 N-m-s momentum storage in roll (bore sight) axis
    - >20 year expected lifetime

Minimum 60 deg slew time

Fast Slew Requirement: 60 deg in 180 minutes

Assumptions:

- Max-acceleration slew with no resisting momentum (½ angle in ½ time)
- Minimum slew time assumes wheel saturation
- Pitch/Yaw: 669 N-m-s momentum storage capability
- Roll: 489 N-m-s momentum storage capability

Pitch and yaw 60 deg minimum slew time is 76 min

Roll 60 deg minimum slew time is 104 min

Sizing Results

Component	Qty	Unit Mass (kg)	Total Mass (kg)	Contingency	Predicted Mass (kg)
Sun Sensor-Coarse	6	1	6	30%	7.8
Sun Sensor-Fine	4	1	4	30%	5.2
Sun Sensor Electronics	4	2	8	30%	10.4
Star Tracker	2	43	86	30%	111.8
Inertial Reference Unit	2	7.1	14.2	30%	18.5
MPS Controller	2	8.5	17	30%	22.1
RCS Controller	1	10	10	30%	13
Reaction Wheels	12	16.5	198	30%	257.4
Disturbance-Free Payload	12	16	192	30%	249.6
Total			**535.2**	**30%**	**695.8**

TECHNOLOGY DEVELOPMENT

Technologies Needing Development

Area	Development needed?	Item
Power	Yes	Telescoping booms for deploying the solar panels/kite tails are very large. AMPS is in development (and baselined in our design); however, other options are available that meet requirements.
GN&C	Possibly	Larger reaction wheels may need to be developed if large, deployable solar array booms are not feasible or desirable.
AR&D	Yes	IF robotic servicing is to be considered, AR&D technology needs to be matured.
Thermal	Possibly	Demonstrate the ability to deploy high conductivity blankets with heaters attached. Demonstrate ability to deploy multiple layers of MLI (sunshade) with heaters attached.

Technologies Needing Development

Area	Development needed?	Item
Communication	**Possibly**	**Laser communications could be beneficial to the design (not baselined here), providing high data rates, but would need development.**
Propulsion	**Possibly**	**On-orbit refueling (demonstrated by Orbital Express, but still needing development).** ***This could be mitigated by carrying enough propellant for the entire mission life.***
Structures	**Yes**	**Active Vibration Isolation System needs development. Additionally, accurately representing the system and its interaction with the observatory structure needs to be addressed.**

Technology Development Needs

- Telescoping boom and drive actuator for solar array panels is novel and requires further analysis and development. Major issues are deployment reliability and dynamic stability after deployment.
- Power electronics are based on Advanced Modular Power System (AMPS) architecture. AMPS is in development now at GRC. Other power electronics systems will certainly meet requirements as well.
- Solar Array panels include reflective portions to be used in directing solar pressure to apply torque to offset solar pressure on main tube. Some research is needed to determine the best method to apply the reflective coating.

COST

Spencer Hill, NASA MSFC Cost Office

Total Costs Phase A-D

WBS	Description	(2015 $ in Millions)
1.0	Optical Mirror Assembly	927 +$250M
2.0	Scientific Instruments	1,250
3.0	Spacecraft	376
4.0	Payload Integration	203
	Reserves	965
TOTAL		**3,720** +$250M

Excludes Launch and Operation Cost

$250M added to OTA to reflect current SOA instead of future SOA. Based on ROM quotes, it is estimated that a 150 kg/m2 primary mirror can be made today for $2 to $3M/m2.

Ground Rules & Assumptions

1. All costs are in Fiscal Year (FY) 2015 dollars in millions based on NASA inflation tables.

2. System Test Hardware (STH) cost represents one equivalent unit, and all applicable system integration (wrap) costs represent the wrap costs for one test unit.

3. All weight data is expressed in kilograms and represents dry weight only.

4. Subsystem costs are limited to prime contractor incurred, exclusive of fee and those costs outside the scope of the prime contractor. Subcontractor effort, including fee in support of the prime contractor effort, is considered prime contractor incurred.

5. Costs associated with the DDT&E effort encompass the period from the beginning of full scale development through factory checkout of the first flight article. Costs associated with the flight article are excluded from DDT&E.

6. Costs associated with the flight unit effort include the period beginning with the start of production initiated by long lead procurements and ending with the delivery of the first unit. Flight unit costs represent only the costs of the first unit to fly.

7. All costs associated with mission operations and facilities are not included.

8. Individual subsystem totals contain all hardware costs and engineering and manufacturing labor costs charged to that subsystem. These totals include all management, engineering, testing, and assembly functions, including the labor, materials, specific test equipment, and ground support equipment associated with the integration of the components or assemblies in the subsystem.

9. Fee and Program Support are set at 10%.

10. Reserves are set at 35%.

11. Vehicle integration, integration at the Cape, is set at 8%.

Optical Mirror Assembly

WBS	Description	(2015 $ in Millions)
1.0	**Optical Mirror Assembly**	**927**+$250M
1.1	**Management & System Engineering**	**92**
1.2	**Primary Mirror Assembly**	**97**
1.2.1	Primary Mirror	42+$250M
1.2.2	Primary Mirror Support Structure	22
1.2.3	Launch Lock Mecanism	33
1.3	**Secondary Mirror Assembly**	**44**
1.3.1	Secondary Mirror	10
1.3.2	Hexpod & Spiders	34
1.4	**Aft Optics Assembly**	**130**
1.4.1	Tertiary Mirriors & Mounts	47
1.4.2	Pupil Mirror & Mounts	31
1.4.3	Fold Mirror & Mounts	52
1.5	**Telescope Structure**	**303**
1.5.1	Straylight Baffles	13
1.5.2	Head Truss & Optical Bench	52
1.5.3	Inner & Outer Sunshields	200
1.5.4	Doors	7
1.5.5	PAF	12
1.5.6	MLI	19
1.6	**Software**	**56**
1.7	**OTE Integration & Test**	**44**
	Fee	**77**
	Government Program Support	**84**

Scientific Instruments

WBS	Description	(2015 $ in Millions)
2.0	Scientific Instruments	1,250
2.1	Management & System Engineering	
2.2	Instrument Bay Structure	24
2.3	Science Instruments Allocation	843
2.4	Facility Instruments Allocation	
2.5	Instrument Integration & Test	166
	Fee	103
	Government Program Support	114

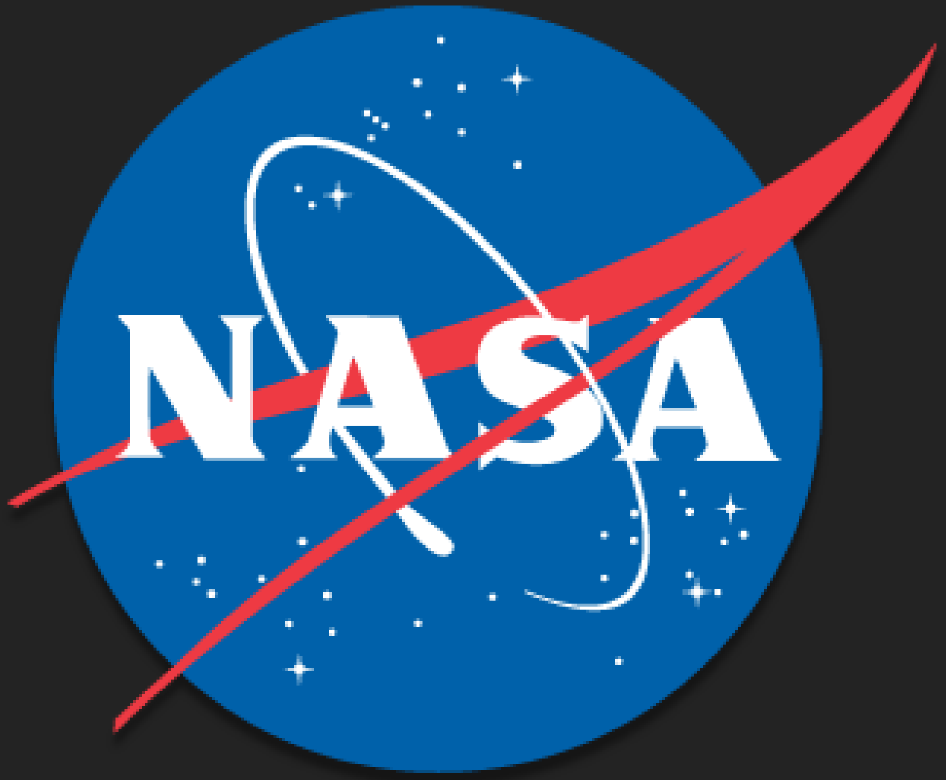
Instrument Costs were taken directly from the Astro2010 RFI and not re-estimated for this study.

Spacecraft

WBS	Description	(2015 $ in Millions)
3.0	Spacecraft	376
3.1	Management & System Engineering	49
3.2	Subsystems	200
3.2.1	Structures & Mechanical	34
3.2.2	Thermal Control	21
3.2.3	Electrical Power	28
3.2.4	C&DH	41
3.2.5	Communication	19
3.2.6	Propulsion	19
3.2.7	Attitude Control	19
3.3	Spacecraft Integration & Test	19
3.4	GSE	46
	Fee	30
	Government Program Support	33

Payload Integration

WBS	Description	(2015 $ in Millions)
4.0	Payload Integration	203
4.1	Optical Telescope Element	74
4.2	Science Instruments	100
4.3	Spraceraft	29



National Aeronautics and Space Administration

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