HabEx Face-to-Face, May 2-4, 2018

Lower Cost HabEx Telescope Concepts

Four and Six Meter On-Axis, and 4 Meter Off-Axis Configurations

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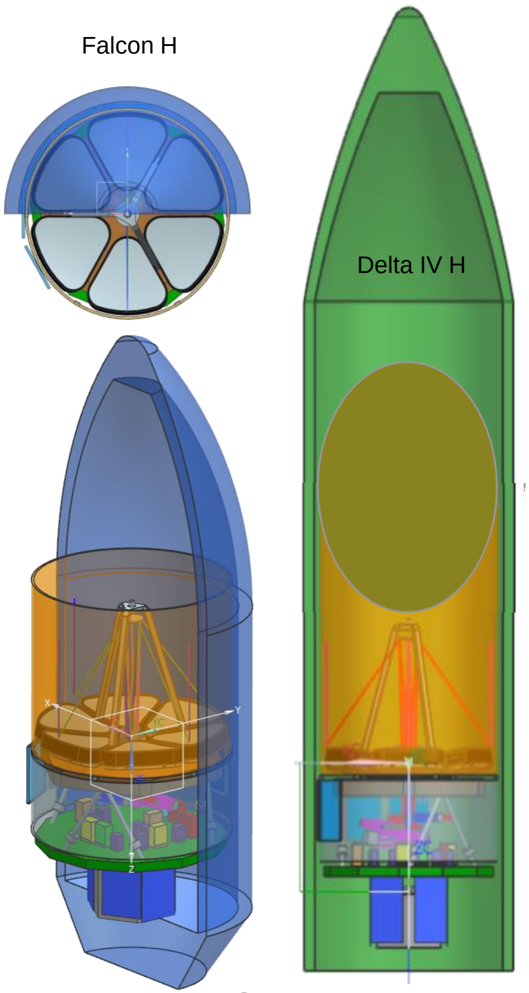
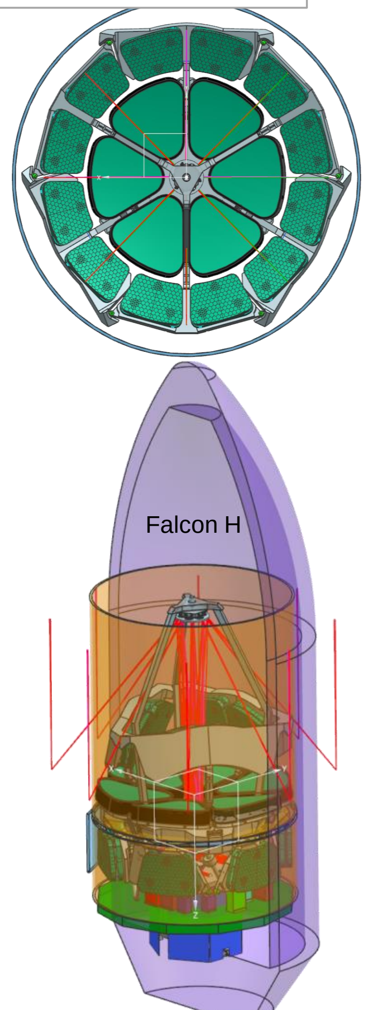
Jet Propulsion Laboratory
California Institute of Technology

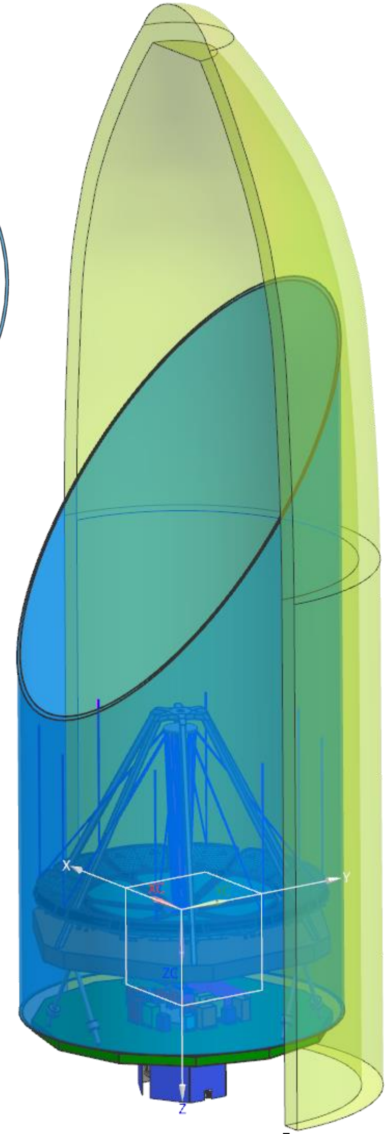
The Low Cost 4 Meter Study



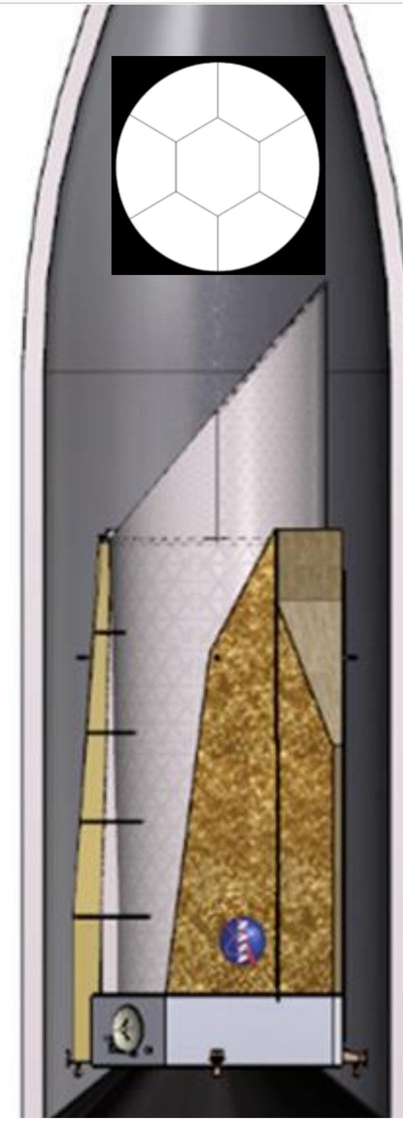
LC4M:
Starshade-only,
Non-deployed OTA,
Falcon H or Delta IV H



LC6M:
Starshade-only,
Deployed OTA,
Falcon H or
Delta IVH



LC6Mnd:
Starshade-only,
Non-deployed OTA,
SLS, BFR,
New Glenn, Vulcan



HabEx4seg:
Coronagraph-compatible
segmented aperture,
Non-deployed OTA,
SLS

LC4M: Design to Cost Approach

- Replace development of monolith with segmented PM
  - Provide 4 m aperture within existing manufacturing capabilities
  - Lower mass than monolith (est ~3x lower mass at PL level)
  - Reduced development and implementation schedule

- Use a Starshade (or 2) to meet HabEx ExoPlanet imaging goals
  - Eliminate the coronagraph, a complex and expensive instrument
  - Eliminate ultra-stability requirements on the observatory

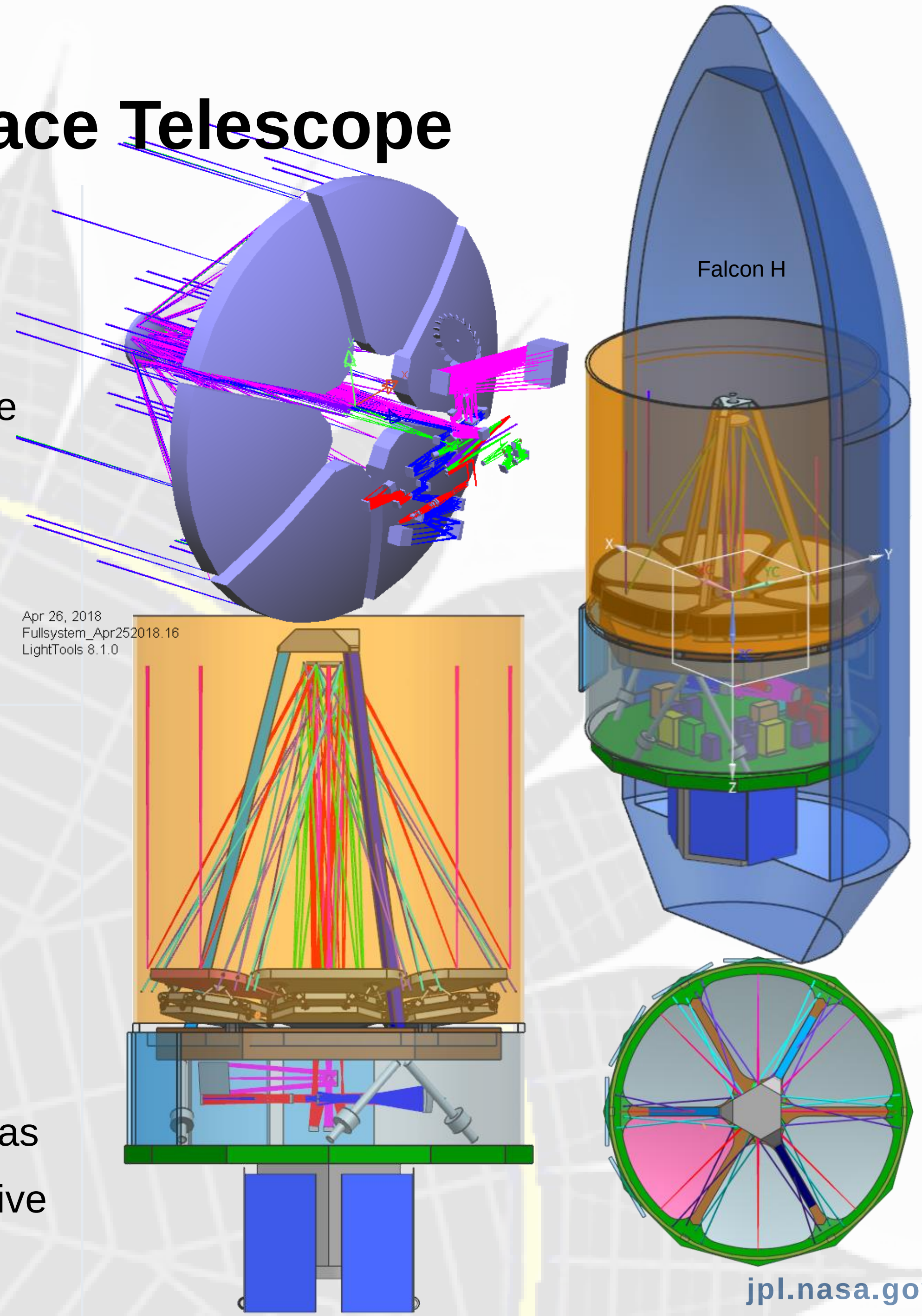
- Use a commercial commodity bus to meet requirements with lower cost and risk
  - Except: consider micro-g thrusters for low-disturbance attitude control

- Design for compatibility with Falcon Heavy or other EELV
  - Non-deployed, segmented primary mirror, fixed Outer Barrel sunshade

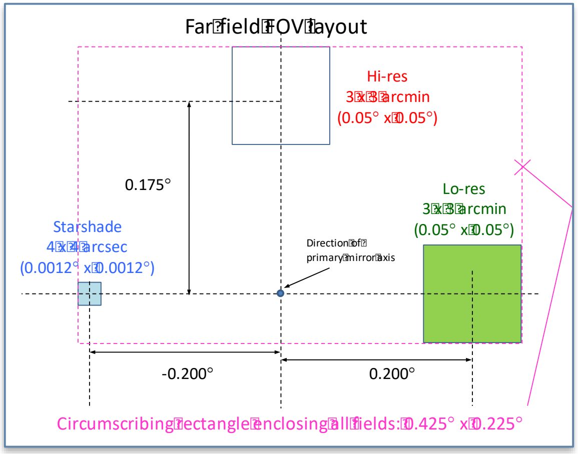
Low Cost 4-Meter Space Telescope

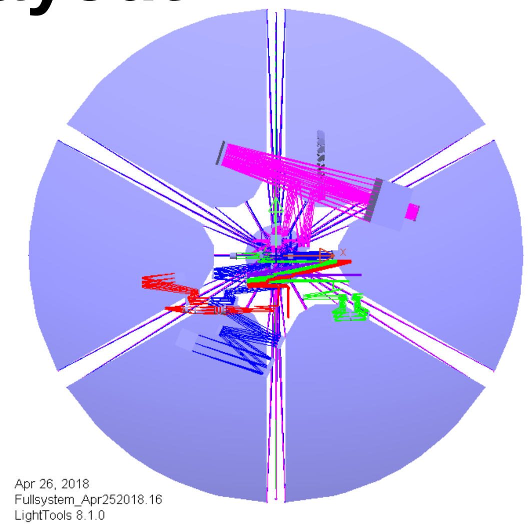
LC4M, aka HabEx Lite

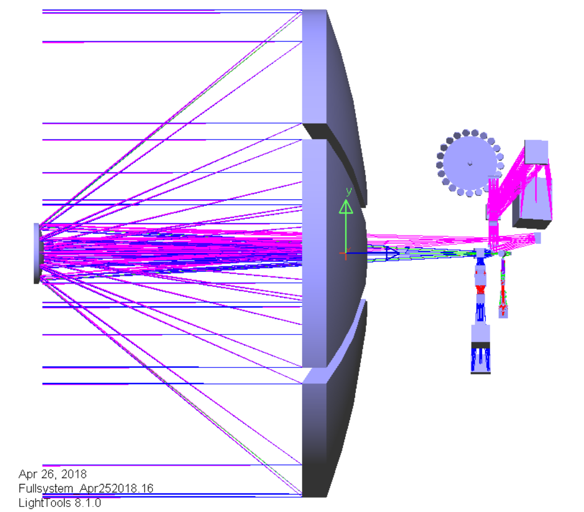
- All HabEx instruments – except Coronagraph
- Starshade performance on par with the baseline Off-Axis HabEx
- exoEarth yield:
  - Single 75 m SS yield is 5-6
  - 36 m SS + 75 m SS yield is 9-10
- Segmented, non-deployed PM uses lightweight glass mirrors
- Mass and volume are consistent with Falcon Heavy or Delta IV H launch
  - Mass CBE = 6425 kg vs 14000 cap
  - Volume = 4.6x11 m (deployed scarf)
- Local thermal control: low power, low mass, low solar array and radiator areas
- Nanometer-level stabilization via passive and active means



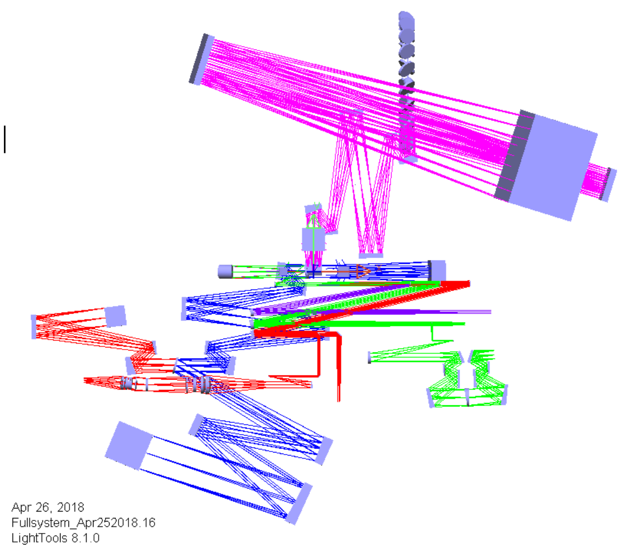
LC4M Optical Layout

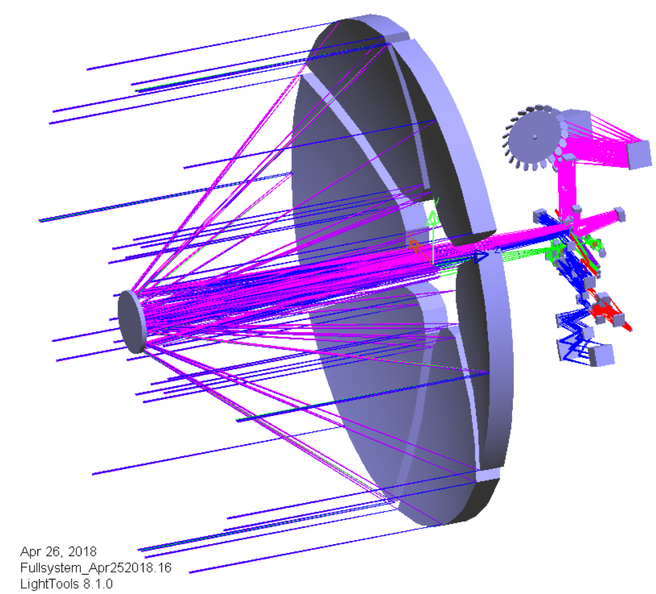




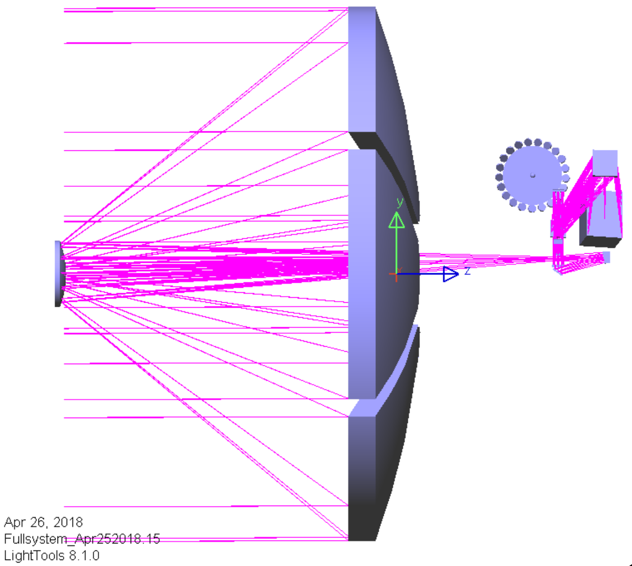


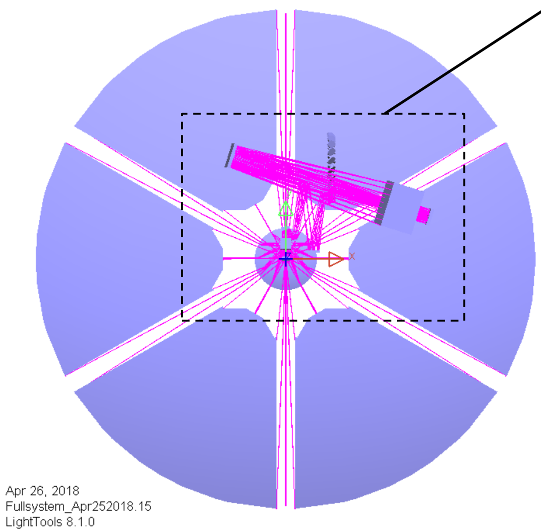
Afocal OTA: M=1/86
PM: 5.6 m ROC, f/0.7
Hi-Res Instrument: UV spectrographs and imagers.
Lo-Res Instrument: UVOI spectrographs and imagers.
Starshade Instrument: UVOIR spectrographs, imagers and guiders.
In total: 8 FPAs, 12 mechanisms.



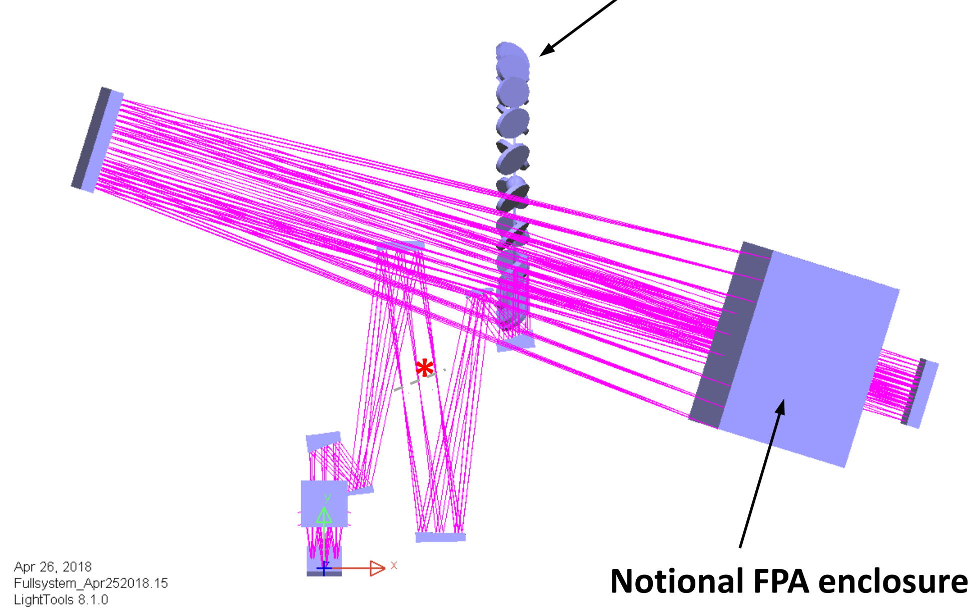


Hi-res channel



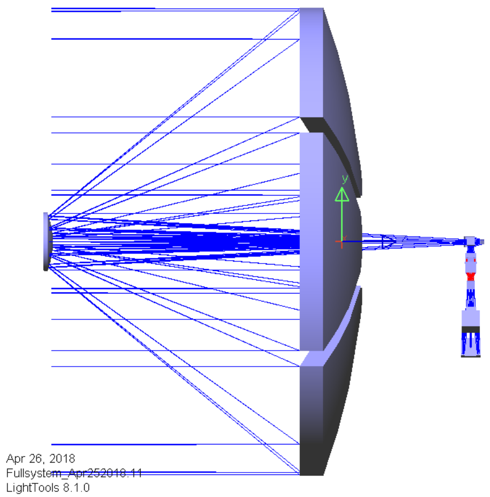


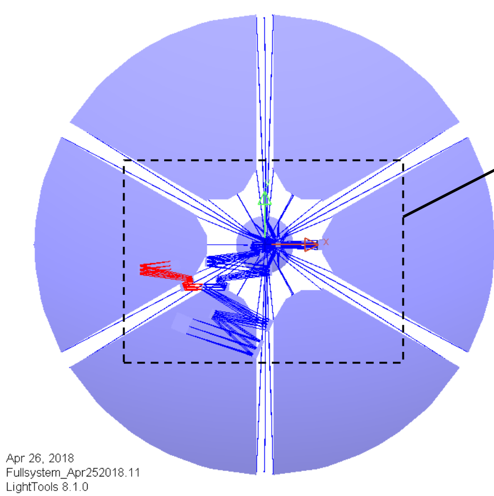
Mechanisms: Filter wheel, Microshutter Array



Hi-res UVS instrument	
Spectral band (nm)	115-300
FOV (arc-min)	3x3
F/# at FPA	F/75
Grating	20 grating settings + 1 flat mirror in a wheel.
Modes	**2:** Spectrograph; imaging.

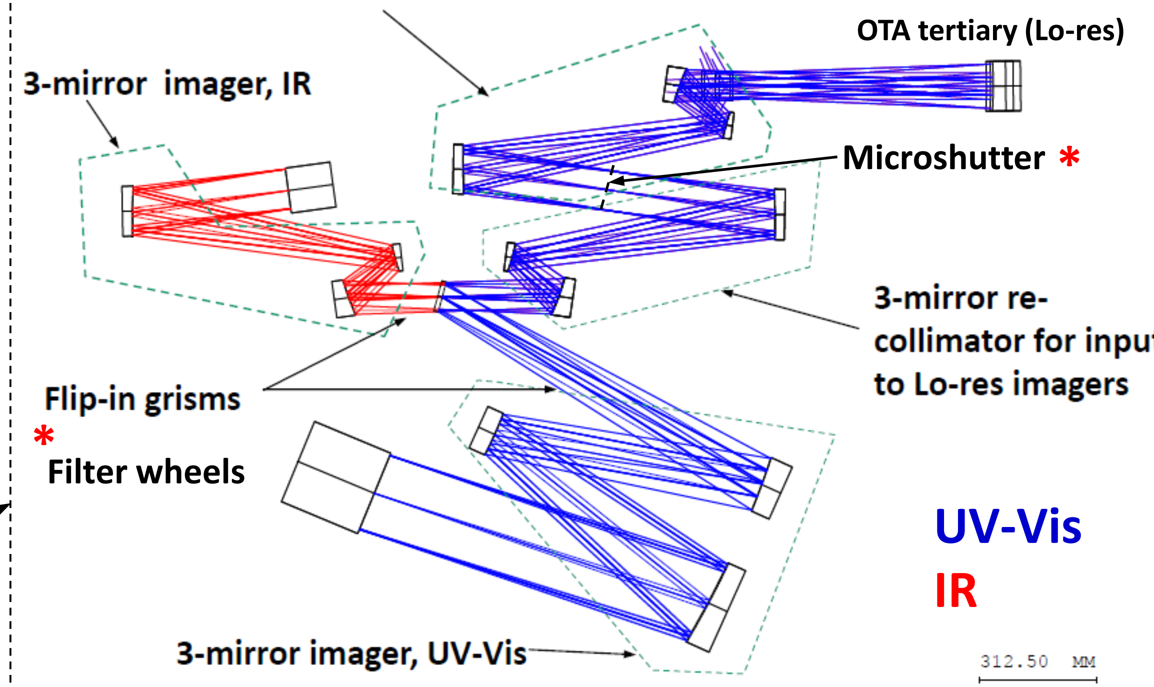
Lo-res channel





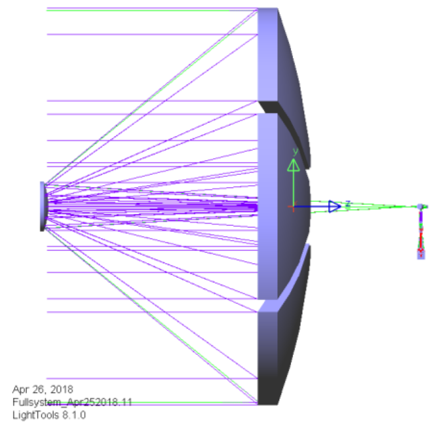
* **Mechanisms:** flip-in grism in both UV-Vis and IR paths; filter wheel in both paths; microshutter array

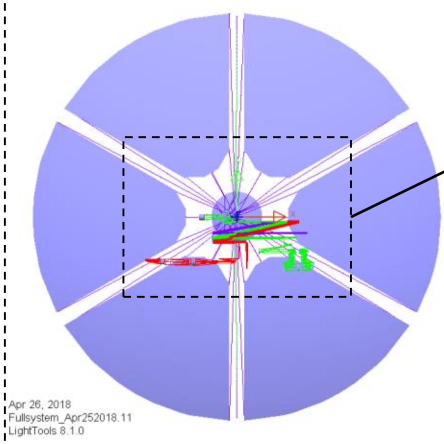
3-mirror imager that takes collimated beam emerging from OTA and forms high-quality telecentric focus at microshutter plane.



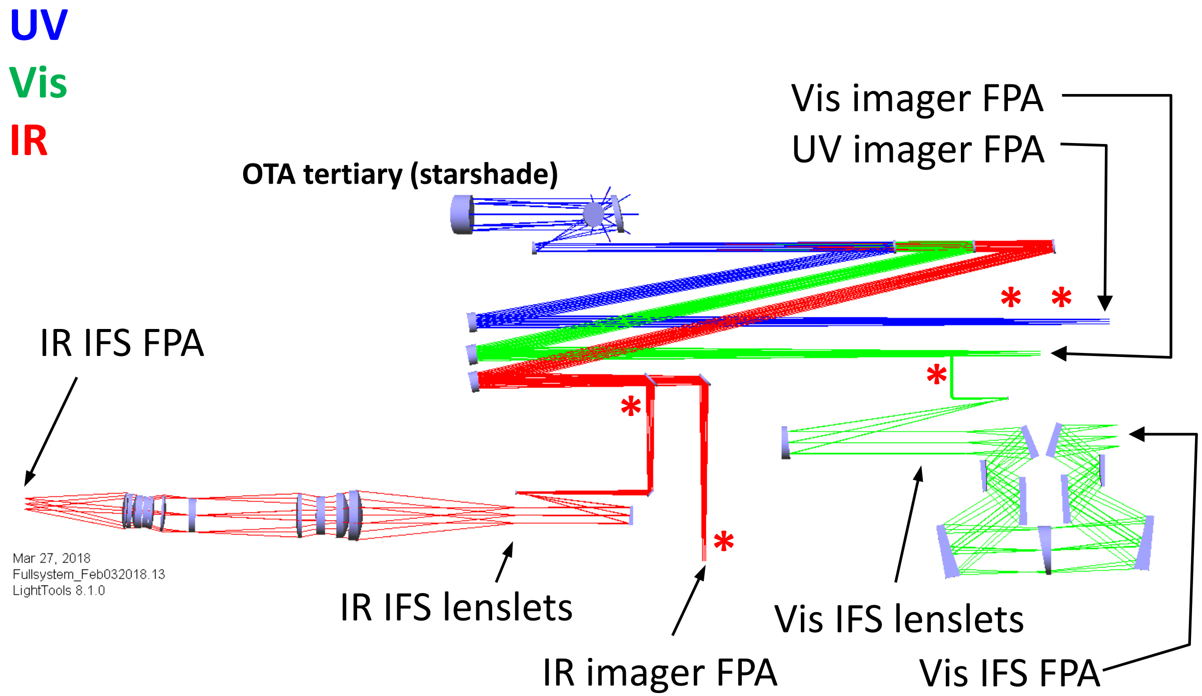
Lo-res instrument [UV-Vis and IR paths]	
Spectral bands (nm)	150-950 UV-Vis; 950-1800 IR
FOV (arc-min)	3x3
F/# at microshutter	About F/20.
F/# at FPA	F/40 (UV-Vis), F/21 (IR).
Modes	**4:** 2 imaging, 2 grisms.

Starshade channel



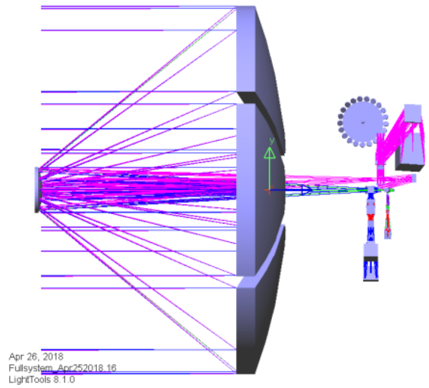


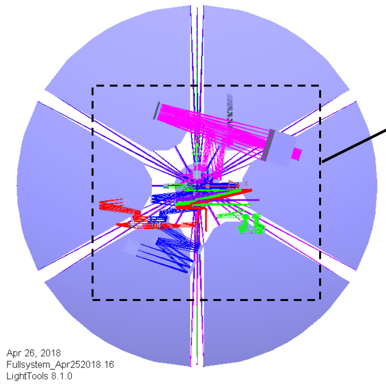
* **Mechanisms:** imaging/IFS switching mirror in Vis and IR; flip-in prism and pupil imaging in UV; pupil imaging in IR

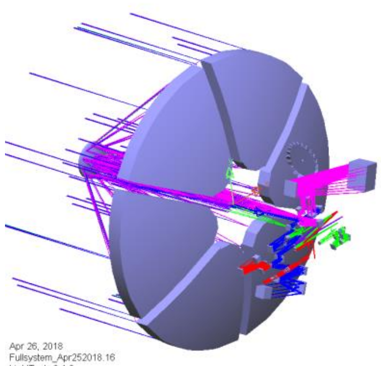


Starshade instrument [UV, Vis, and IR paths]	
Spectral bands (nm)	200-450 UV; 450-1000 Vis; 975-1800 IR.
FOV (arcsec diameter)	7.0 UV, 7.9 Vis, 7.9 IR.
F/# , imaging	90 UV, 71 Vis, 51 IR.
F/#, IFS	6.0 Vis, 3.36 IR.
Modes	**8:** 3 star imaging, 2 pupil imaging (UV and IR), 2 IFS (Vis and IR), 1 spectrograph (UV)

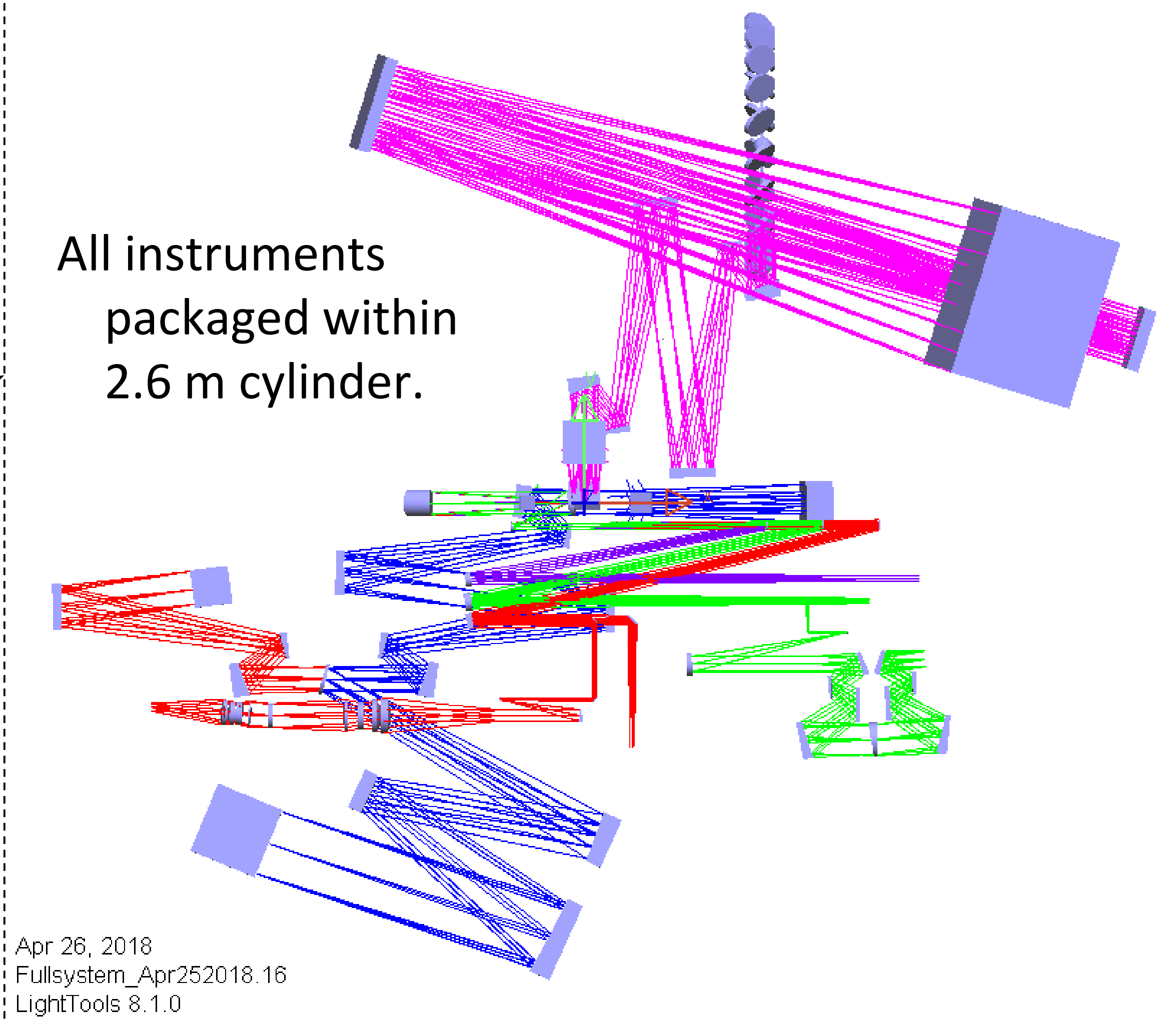
OTA with all instruments







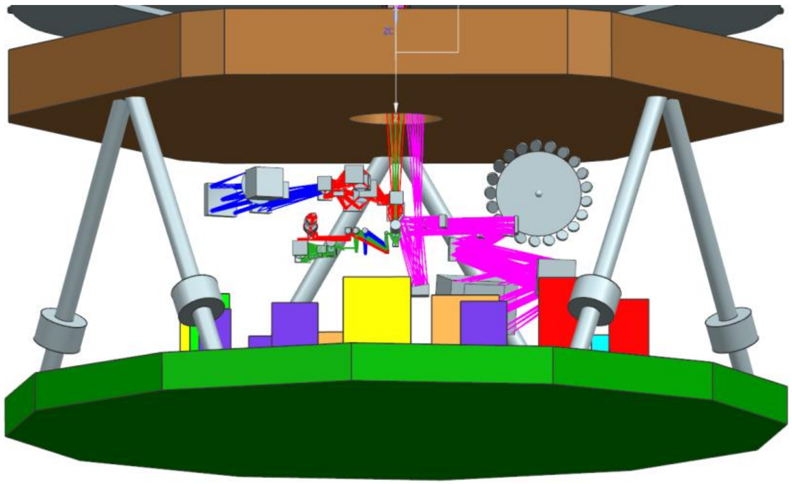
All instruments packaged within 2.6 m cylinder.

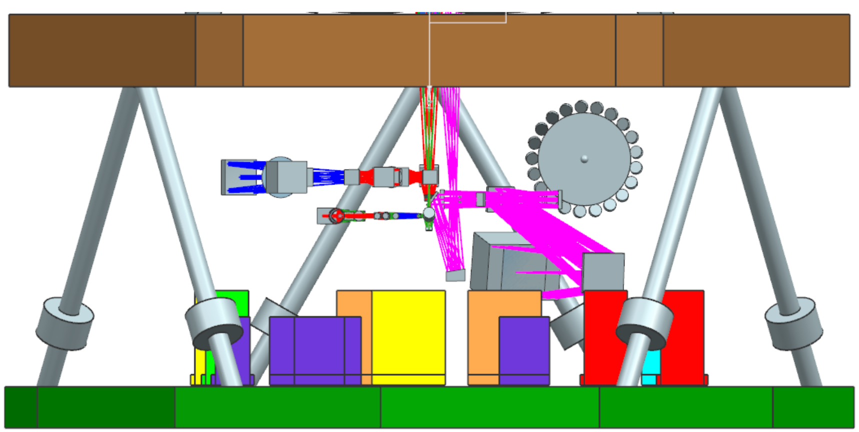


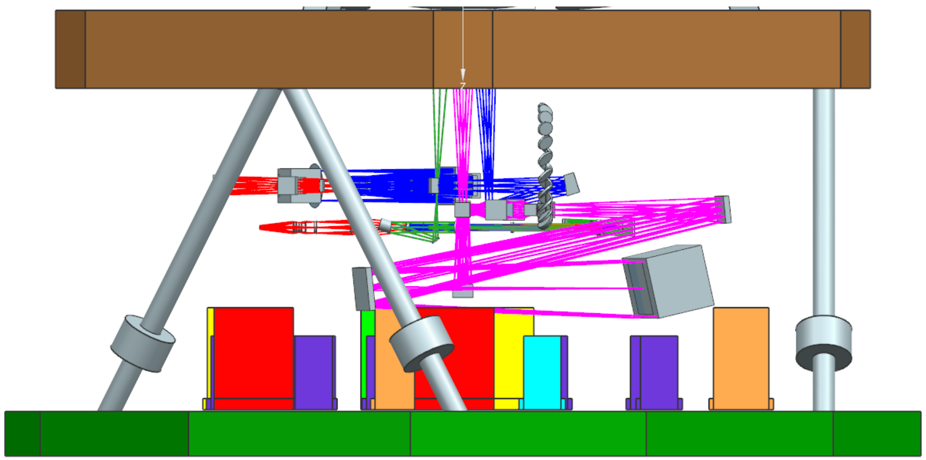
LC4M Payload Packaging

- Details...

- 2 red boxes for thermal – 12 card 9U type
- 2 yellow boxes for FCA – 10 card 9U type
- 1 blue box for deployment/latching – 8 card 6U type
- 1 green box for RBA – 10 card 9U type
- 8 purple boxes for instruments – 8 card 6U type
- 2 brown boxes for metrology – 10 card 9U type
- Total of electronic boxes: 16

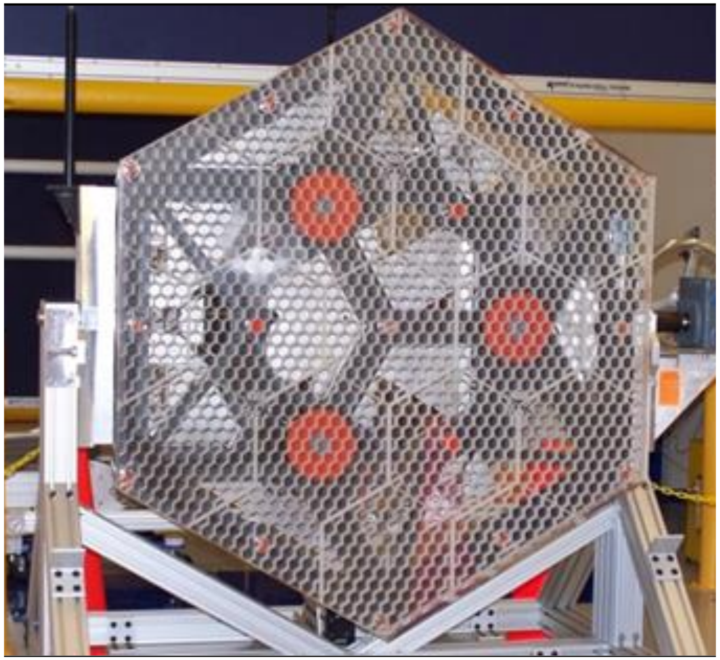


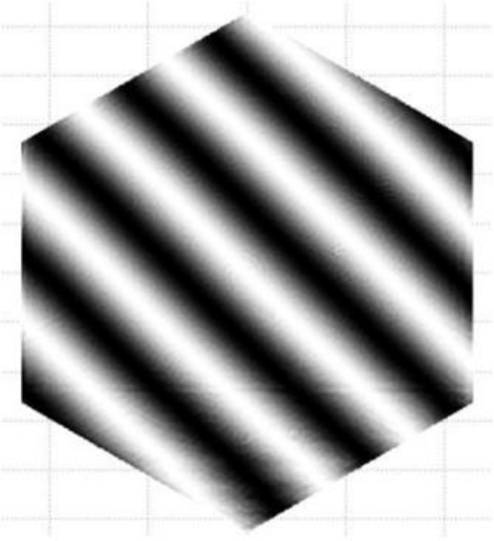


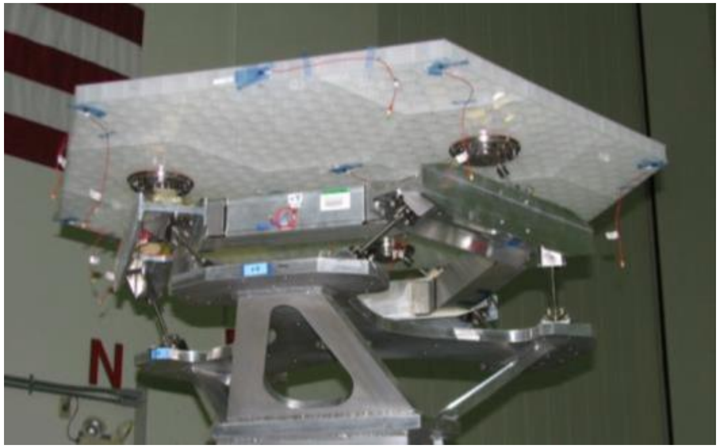


ULE Mirrors: Demonstrated Performance

- MMSD: low substrate mass: 10 kg/m^2
- WF error:
  - 15 nm RMS WFE stand-alone, with backouts
  - 8 nm WFE RMS post-actuation predicted
- Survivability tested to high level
  - Random vibe and shock

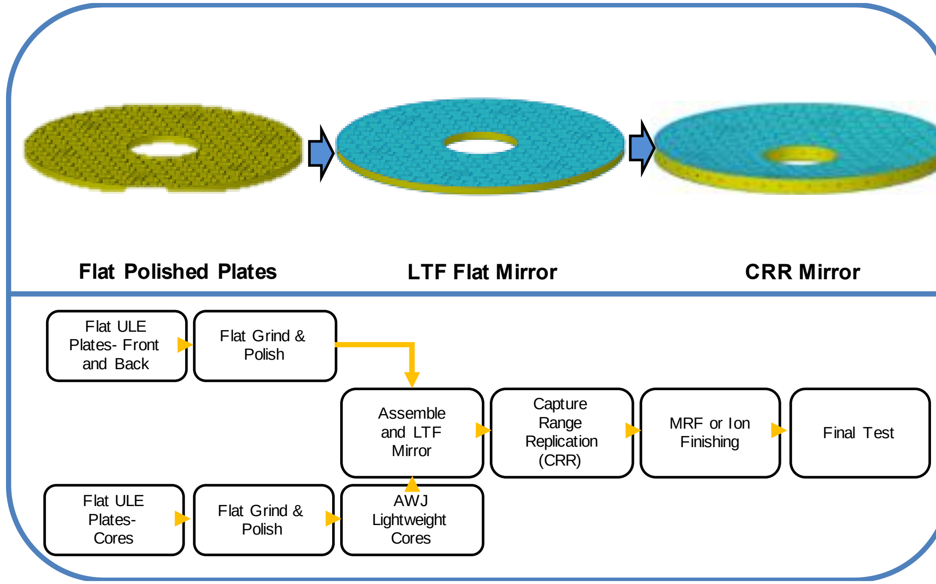




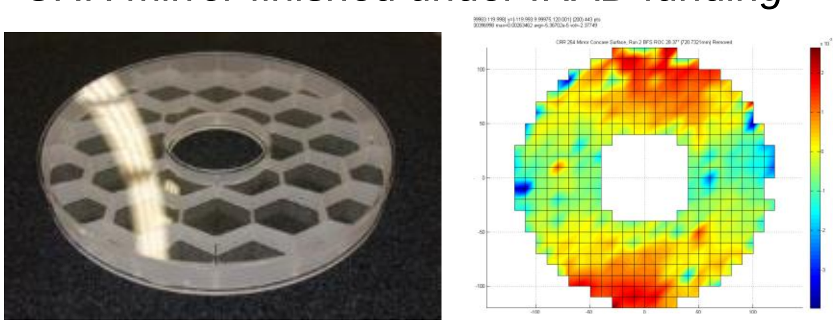


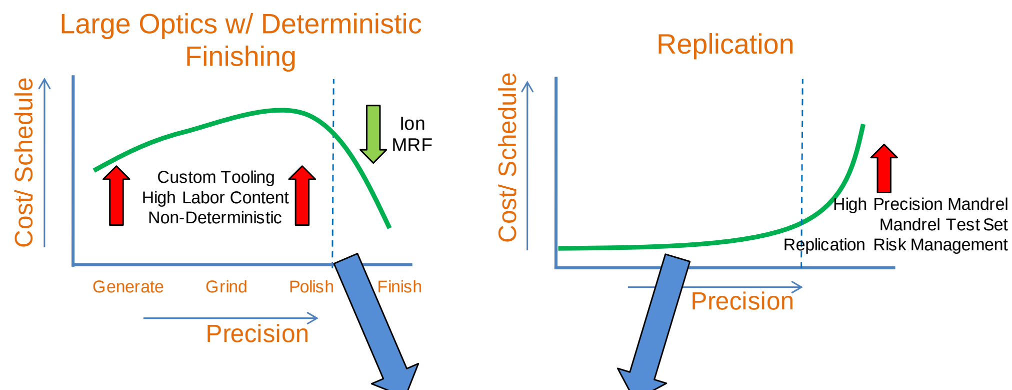
Harris Capture Range Replication

- Capture Range Replication uses precision mandrels and low-temperature slumping to replace traditional generate-grind-polish processes
- CRR finishes a mirror blank to within capture range for final finishing (MRF or Ion Beam)
- Result is a repeatable, efficient process for mirror fabrication, saving time and cost



CRR mirror finished under IRAD funding

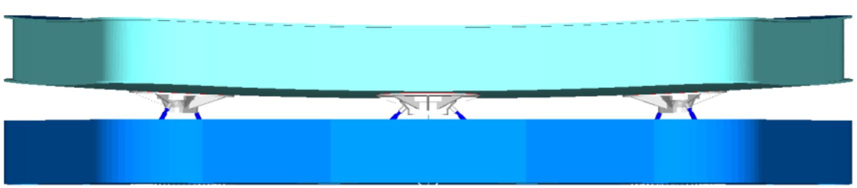




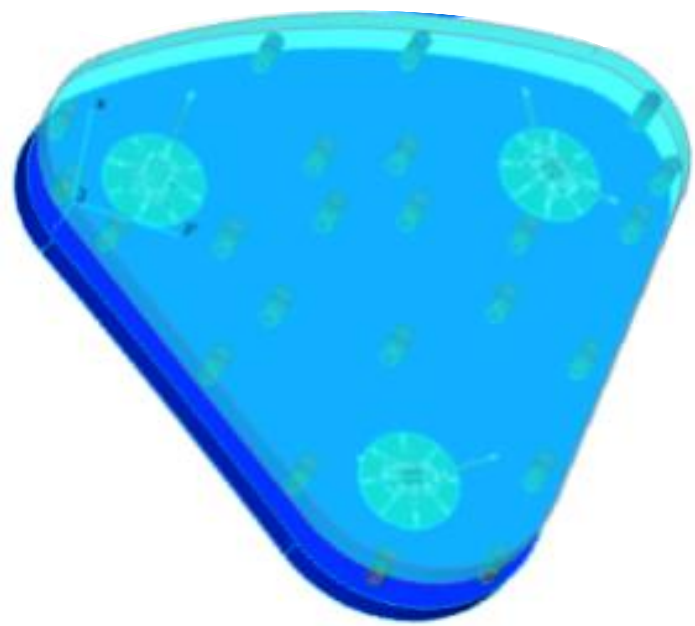
Capture Range Replication (CRR) leverages the strengths of replication to eliminate the high cost/ schedule processes in optical fabrication to provide an optimized solution

Mirrors for Segmented HabEx

- Low-authority architecture uses ~24 FCAs to compensate the most challenging fab errors
  - Meet 10 nm RMS figure error over full PM using current processes
  - Enable use of 3DOF rigid-body actuators for smaller gap
- FCAs also provide on-orbit correctability of system-level errors
- FCAs use constant-force design for insensitivity to thermal deformation
- When coupled with stiff substrate, FCAs partially compensate gravity sag for improved testing

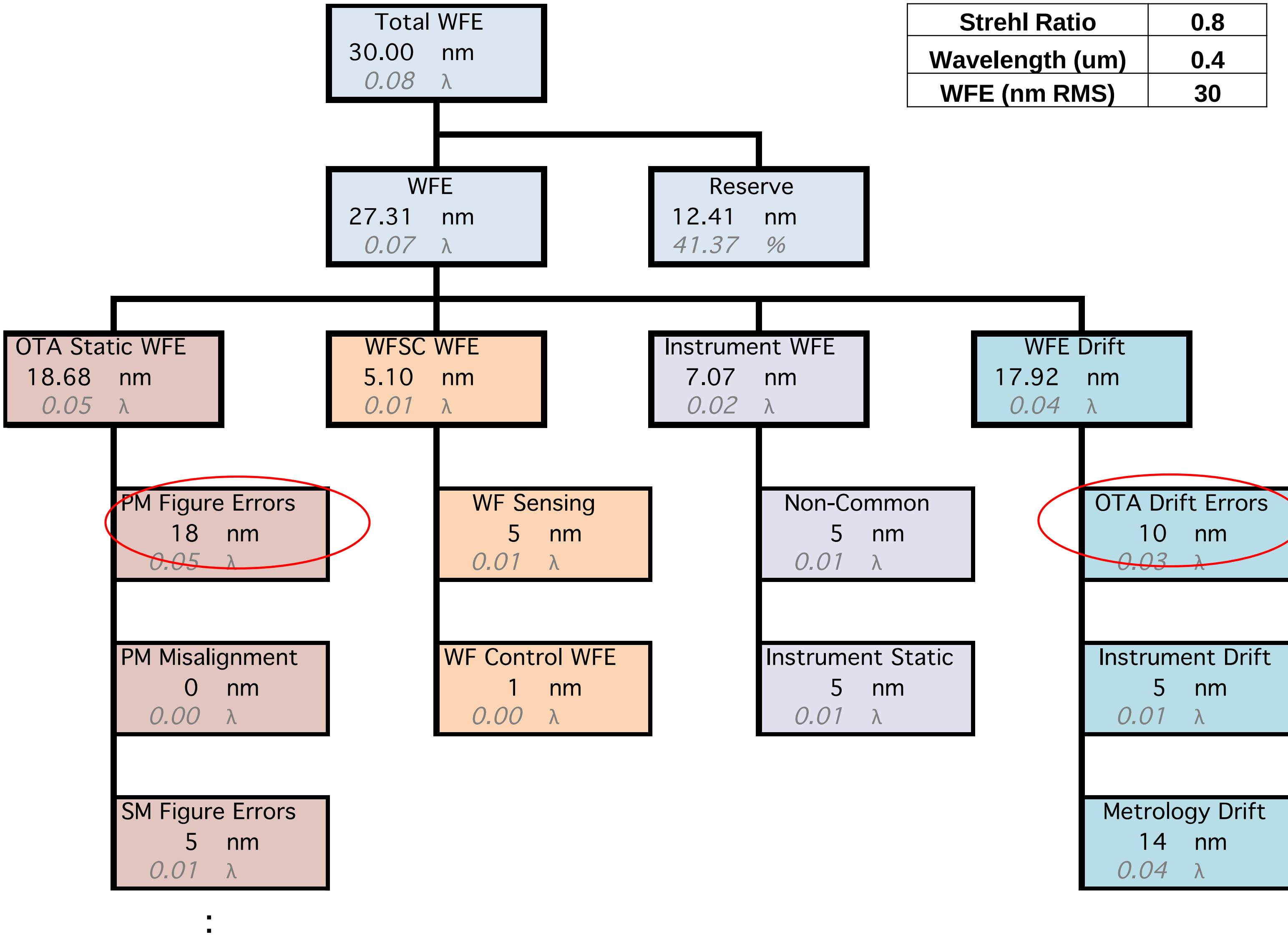


- Passive glass segments meeting 10 nm RMS surface figure error may also be possible with further mfg. process development
  - To reduce ROC-matching errors
  - To improve 0-g figure prediction
  - Will require 6DOF RB actuation

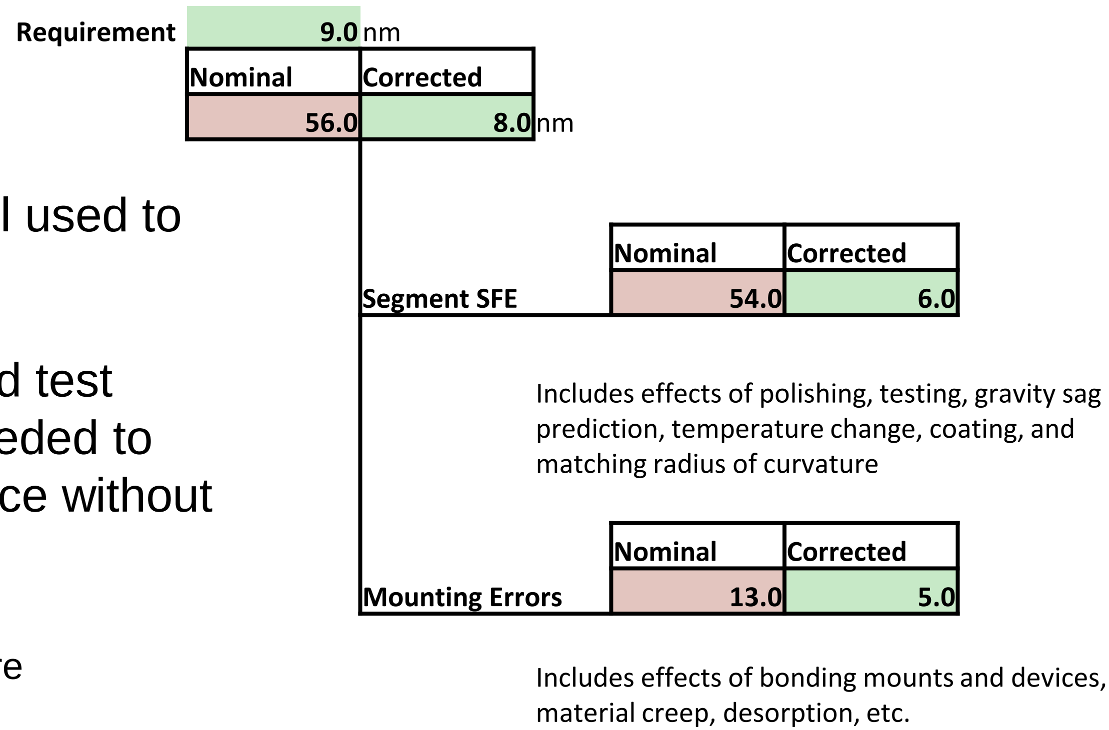


LC4M Wavefront Error Budget

Strehl Ratio	0.8
Wavelength (um)	0.4
WFE (nm RMS)	30



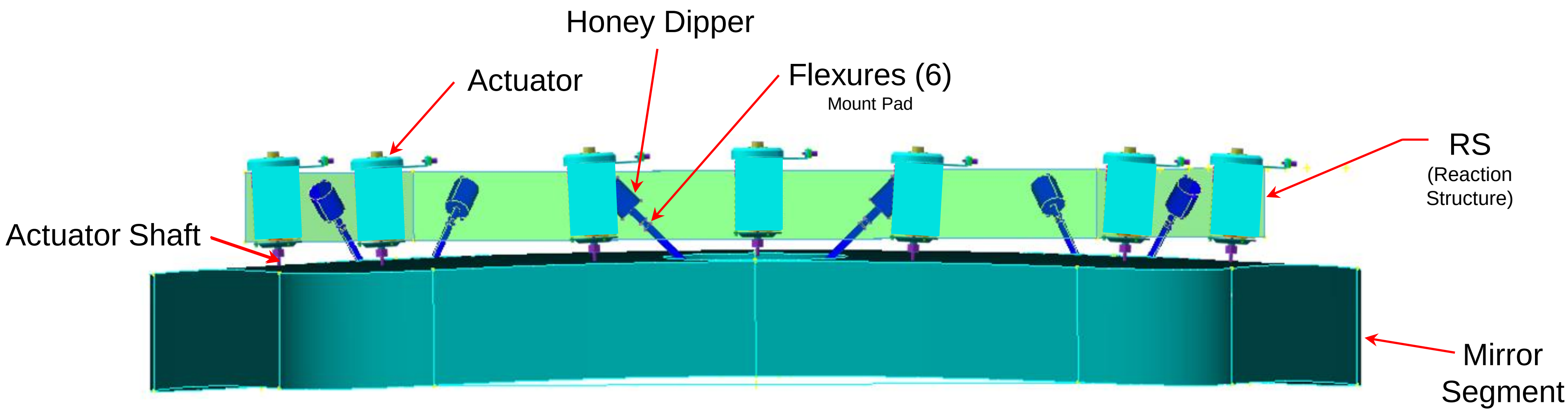
Preliminary Primary Mirror Error Budget



- Low-order PM figure control used to meet 9nm SFE
- Segment manufacturing and test improvements would be needed to provide required performance without actuation
  - Improved RoC matching
  - Testing at operational temperature
  - Improved 0-g testing techniques
- However, the ability to perform on-orbit corrections mitigates risk and uncertainty in final performance

Manufacturing WFE Budget: Using Figure Control to Meet PM Allocations – and Reduce Risk

Optic and Actuator Layout



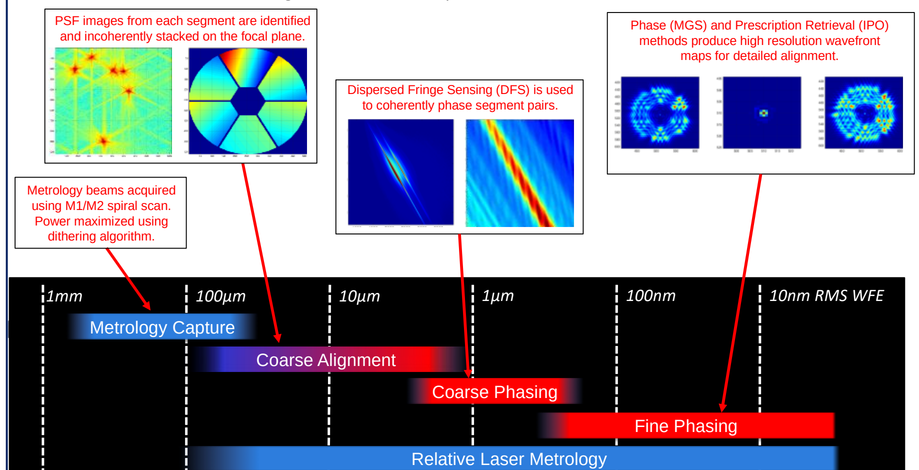
- Side view of mirror, showing glass segment facing down, with Reaction Structure

Wavefront Sensing and Control (WFSC)

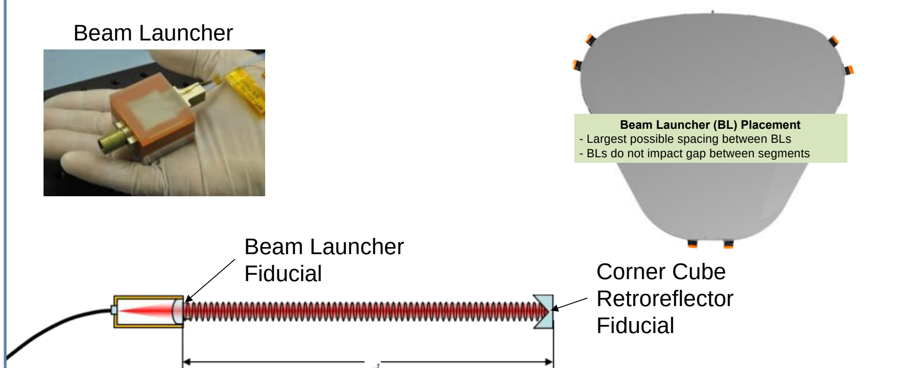
- Wavefront Sensing and Control (WFSC) establishes exquisite optical quality after launch
- Laser Truss metrology (MET) preserves optical quality during all operations

Commissioning and Initial Alignment

- Image-based sensing methods are used to align the telescope after launch and achieve initial, diffraction limited performance.
- Detailed commissioning timeline in development.



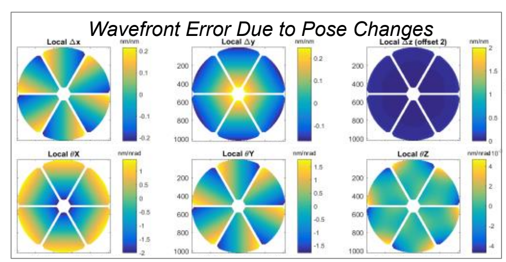
Laser Metrology Overview

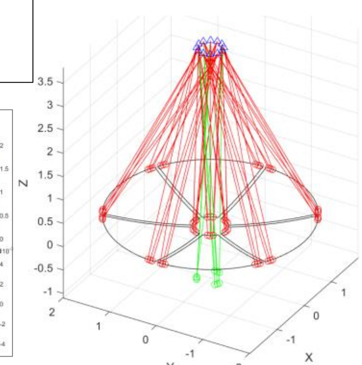


- A collimated beam from the Beam Launcher (BL) propagates through free space and to a corner cube, then back to the BL where it couples back into fiber optics.
- A portion of the beam is also reflected from the BL and coupled back into the optic fiber.
- A heterodyne technique is used to measure changes in the phase between the two paths.

Laser Metrology Truss

- 6 or 9 Laser gauges per optic
- Optic is referenced to the optic bench
- Excellent sensitivity in the optically significant degrees of freedom (θ_X, θ_Y, ΔZ)





Pose Uncertainty per nm of laser gauge uncertainty (9BL Config)						
	ΔX	ΔY	ΔZ	θ_X	θ_Y	θ_Z
Segment (nm or nrad)	8.2	10.4	0.50	2.6	2.2	8.6
SM (nm or nrad)	8.8	9.1	0.33	2.1	1.8	30.6

LC4M Primary Mirror Total Mass

- **The areal density of the mounted mirror assembly is expected to be 34.2 kg/m^2**
  - 44.4 kg/m^2 with 30% mass contingency
  - The mass includes all elements listed in the table
    - Mirrors, mounts and structures
    - Passive & active thermal controls
    - Electronics and cables
- **The least mature term in the mass budget is the reaction structure (backplane), which reflects the total mass of six MCS-like structures**

Mass is consistent with a system mass within existing launch vehicle capabilities

Total LC4M Mass (Six Mounted Petals)

(No Mass Contingency)

Sub-Assembly	Mass (kg)
Glass	186
Mount Pads	43.2
Reaction Structure (Backplane)	49.2
Rigid Body Actuators (6 per mirror)	37.6
Surface Figure Actuators	25.2
Potting Cups	2.9
Beam Launchers	5.4
Electronics	23
Cabling	13
Flexures (6 per mirror)	0.7
Total PMA Mass (6 Petals)	**386.2**

Mounted Mirror Assembly Areal Density (kg/m^2) (No Mass Contingency)	**34.2**

LC4M Preliminary Mass Estimate

Element Name	ASM PARENT	Qty	Material	CBE Mass /Unit (Kg)	CBE MASS (kg)	JPL Uncertainty Factor	CBE Mass+JPL Uncertainty Factor
HABEX SEGMENT TELESCOPE Assembly (4m--6 Segment)	HABEX ASSY	1			**2901.8**	**1.33**	**3848.4**
Primary Mirror ASM	HABEX ASSY	1			386	1.3	502.0
Secondary Mirror ASM	HABEX ASSY	1			63	1.3	82.0
Flat Fold Mirror ASM	HABEX ASSY	1			1	1.3	1.4
Tertiary Mirror ASM	HABEX ASSY	1			1	1.3	1.3
Tertiary Mirror ASM 2	HABEX ASSY	1			1	1.3	1.3
IFU FOLD Mirror ASM	HABEX ASSY	1			0	1.3	0.6
IFU Mirror ASM 1	HABEX ASSY	1			0	1.3	0.6
IFU Mirror ASM 2	HABEX ASSY	1			0	1.3	0.6
IFU ASM	HABEX ASSY	1			127	1.3	164.5
NFOV ASM	HABEX ASSY	1			127	1.3	165.2
WFOV ASM	HABEX ASSY	1			127	1.3	165.2
Electronics Assy	HABEX ASSY	1			485	1.3	630.5
Aft Metering Structure (AMS) Assy	HABEX ASSY	1			306	1.3	397.2
Seconadry Support ASM	HABEX ASSY	1			195	1.3	253.5
Core Structure ASM	HABEX ASSY	1			228	1.3	295.8
Barrel Assembly	HABEX ASSY	1			228	1.3	295.8
Radiator Assembly	HABEX ASSY	1			137	1.3	177.7
Telescope to SC Strut ASM	HABEX ASSY	1			142	1.5	212.6
Cabling Assembly	HABEX ASSY	12			275	1.5	412.5
Dust Cover Assembly	HABEX ASSY	1			73	1.2	87.9
Spacecraft Bus Assembly					**2050**	**1.10**	**2265**
Launch Vehicle Assembly					**725**	**1.35**	**976**
Launch Dry Mass (inc. LV Interface)					5402		6778
BOL Mass (post Transfer Orbit)					5227		6425

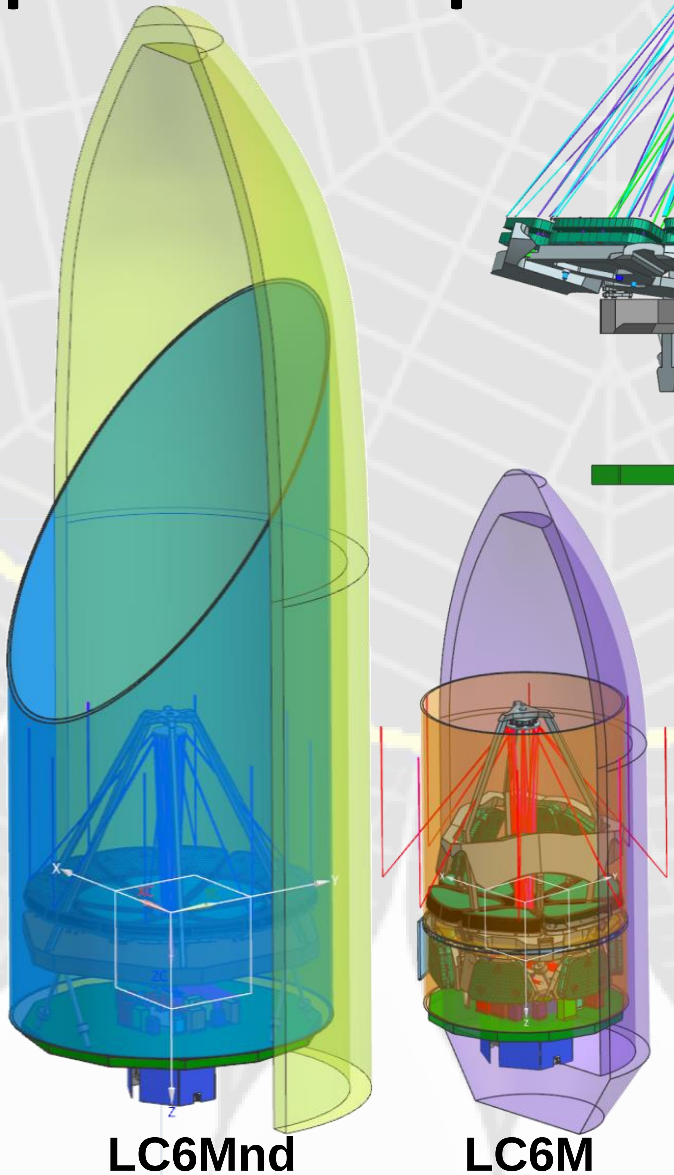
Mass to C3

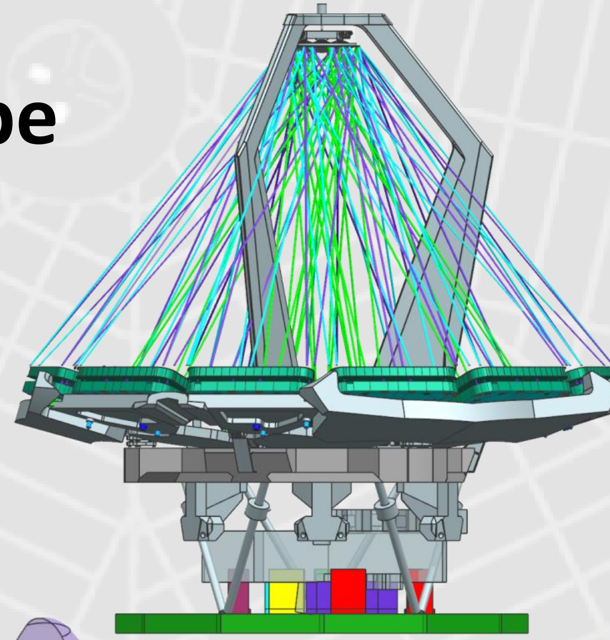
Atlas V 551	6,100 kg
Delta IV Heavy	9,800 kg
Falcon 9 Heavy	14,000 kg
New Glenn 3	17,000 kg

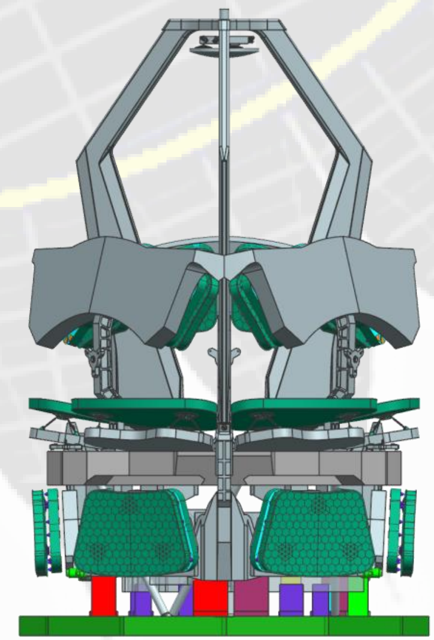
Low Cost *6*-Meter Space Telescope

- LC6M and LC6Mnd

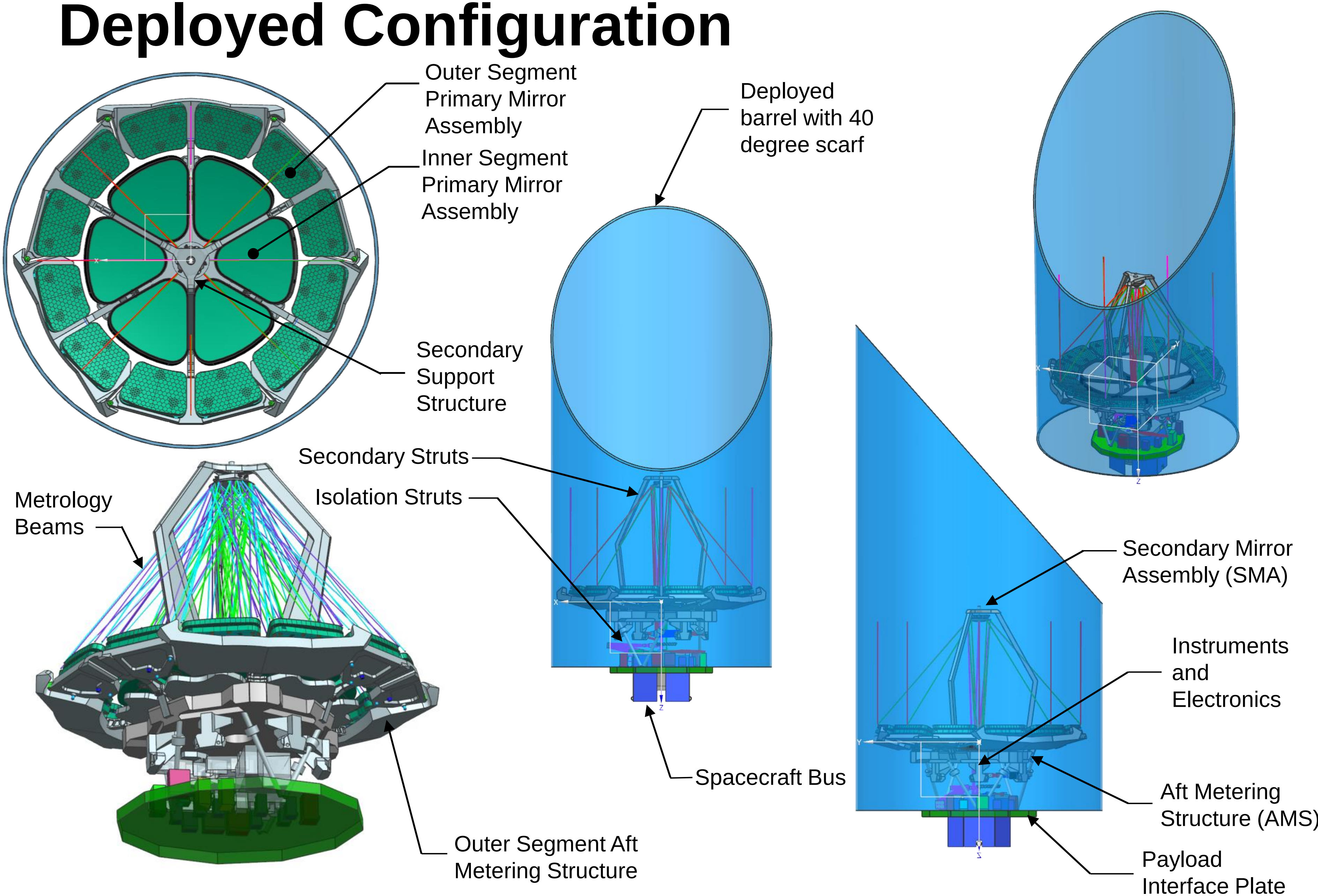
- All HabEx instruments – except Coronagraph
- Lightweight mirrors
- Local thermal control for low power
- Nanometer-level stabilization via passive and active means
- Two variants:
  - **LC6M**: Segmented, deployed PM, with deployed barrel sunshade
    - Launch by Falcon Heavy or other EELV
  - **LC6Mnd**: Non-deployed PM and barrel sunshade
    - Launch by SLS, BFR, New Glenn, Vulcan or other future LV



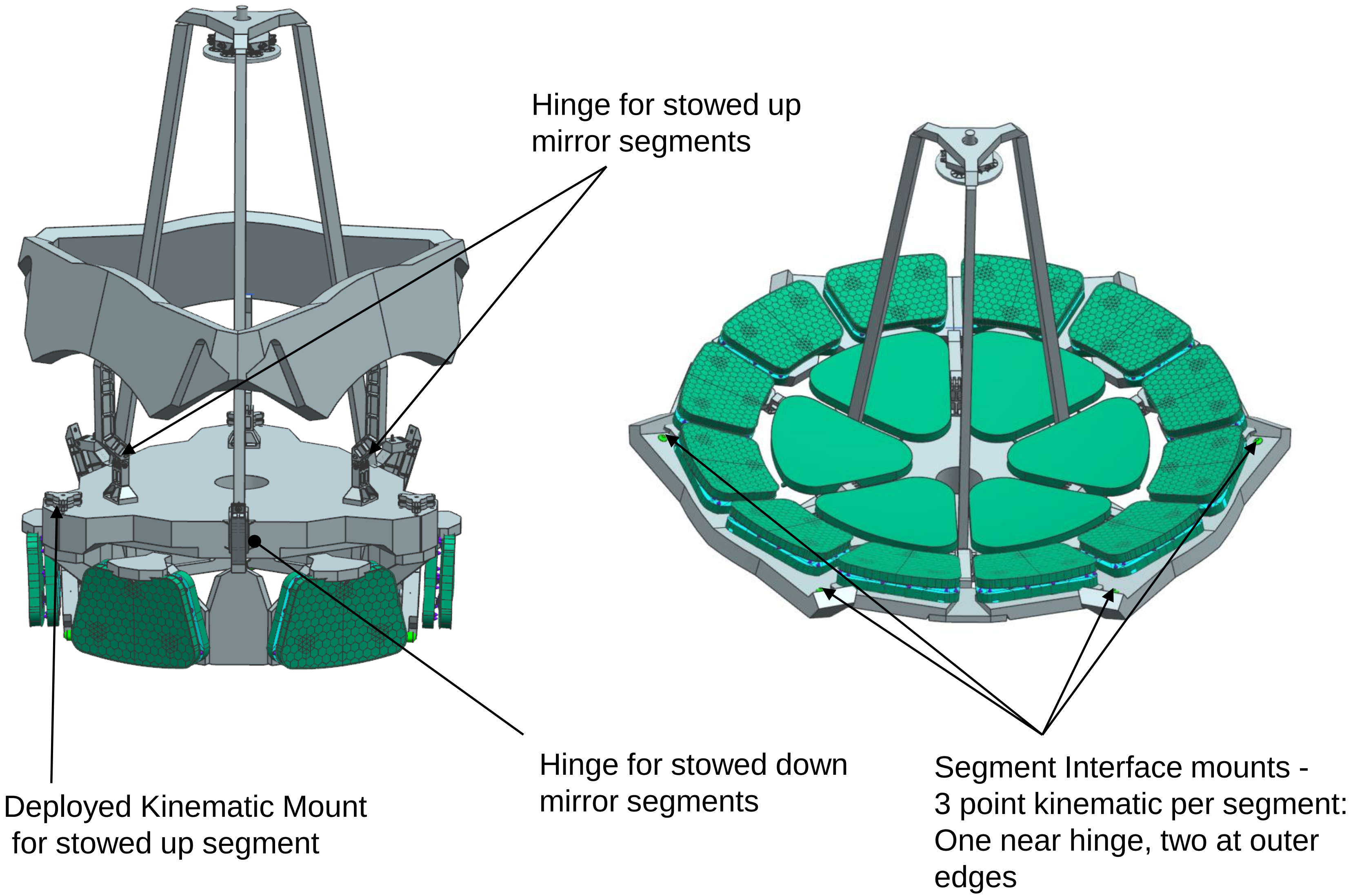




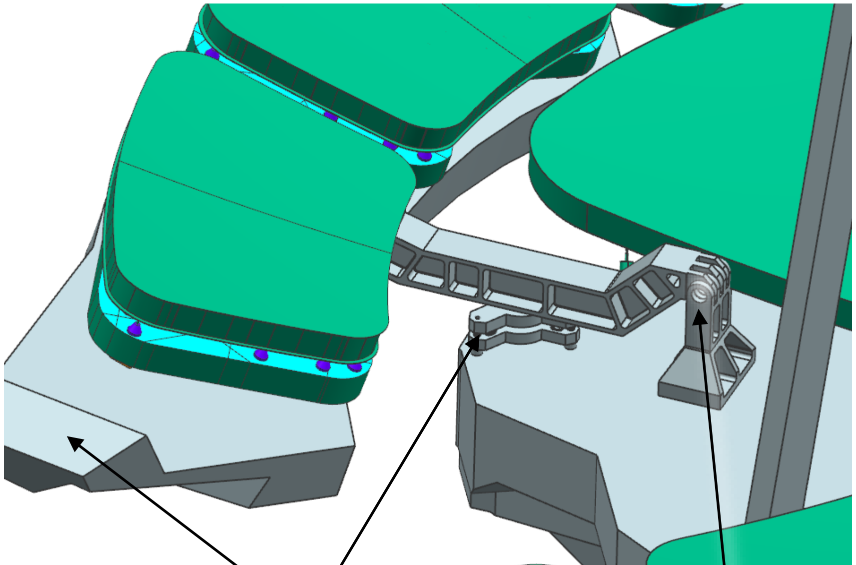
Deployed Configuration

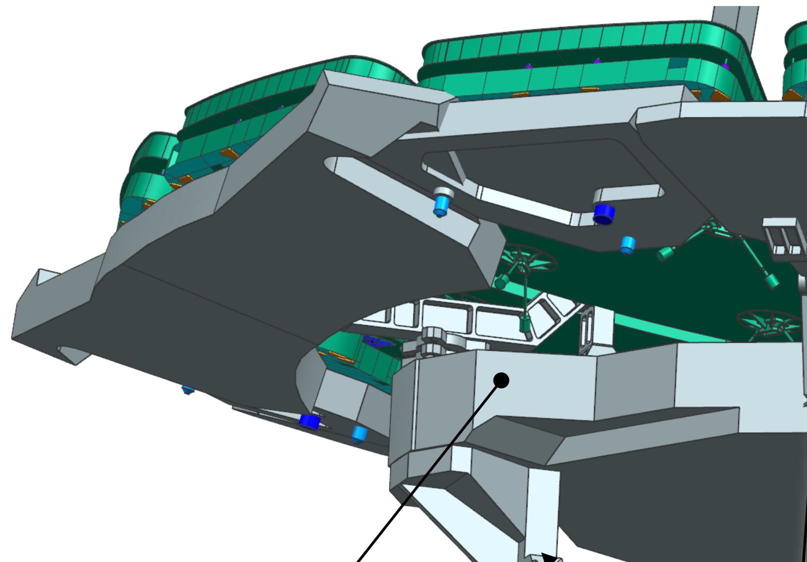


Up-Down Deployment



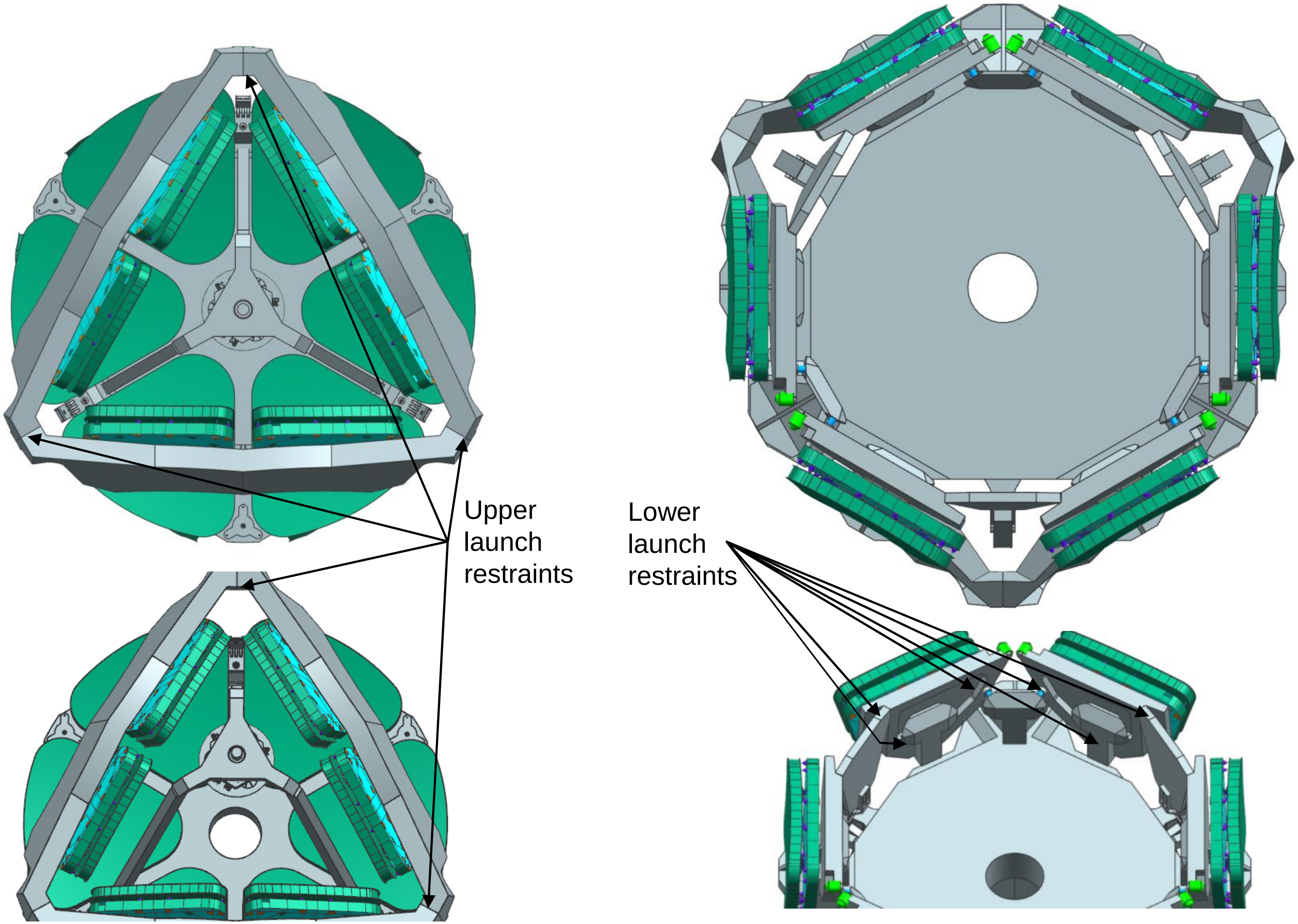
Aft Metering Structure



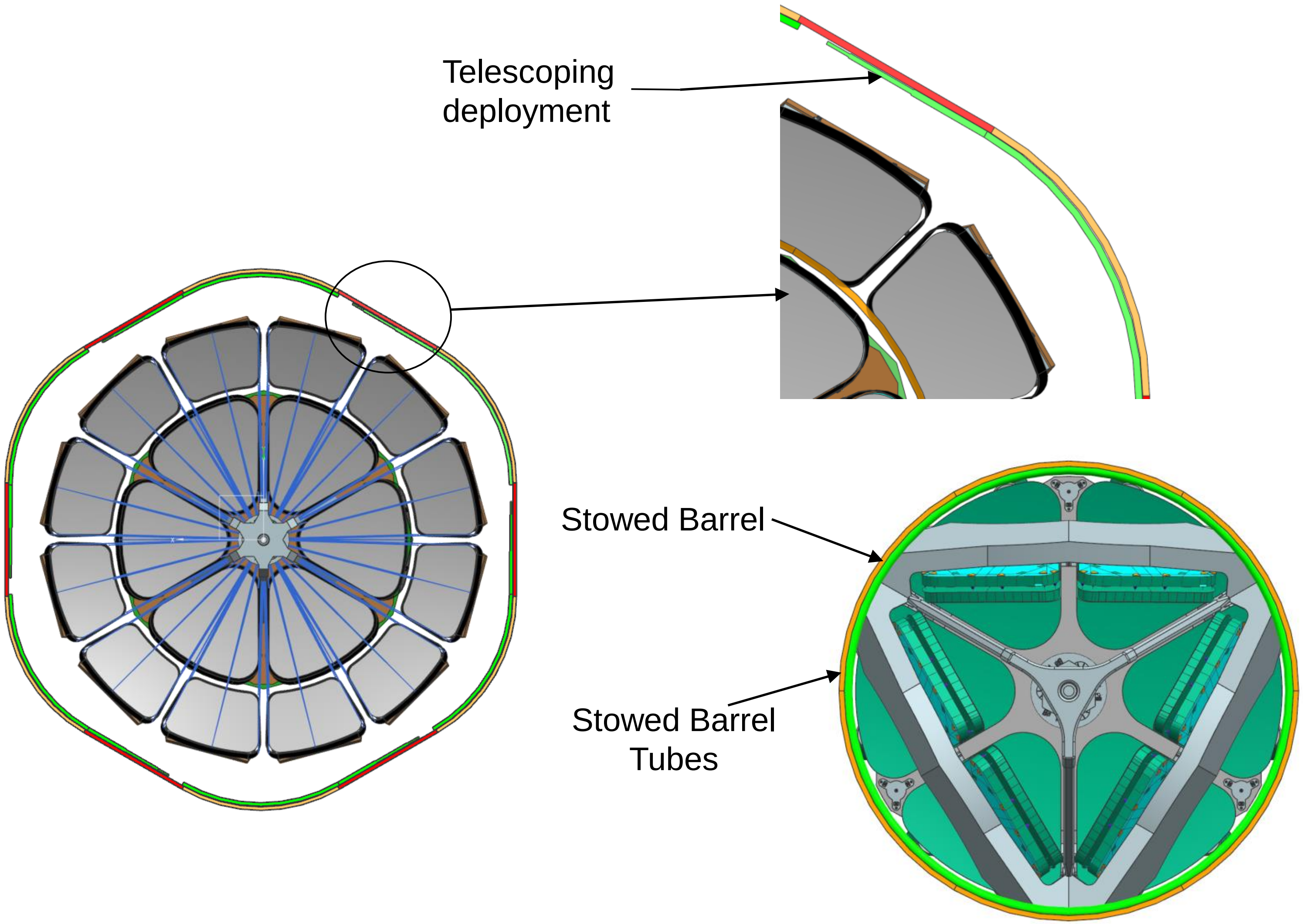


- Segments secured in both launch and deployed configuration by latches that secure backup structure
- Hinges help support during launch, but are out of load path in deployed configuration

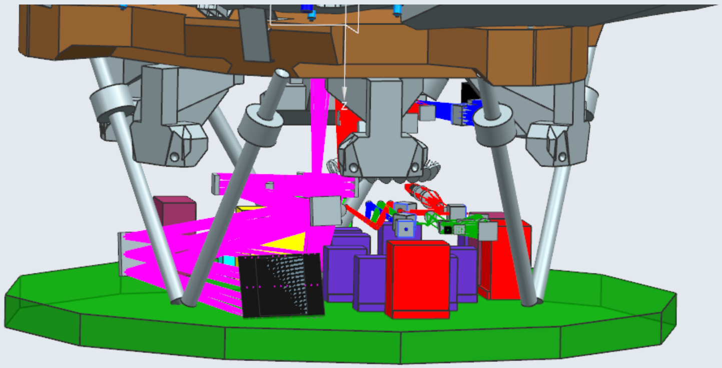
Launch restraints

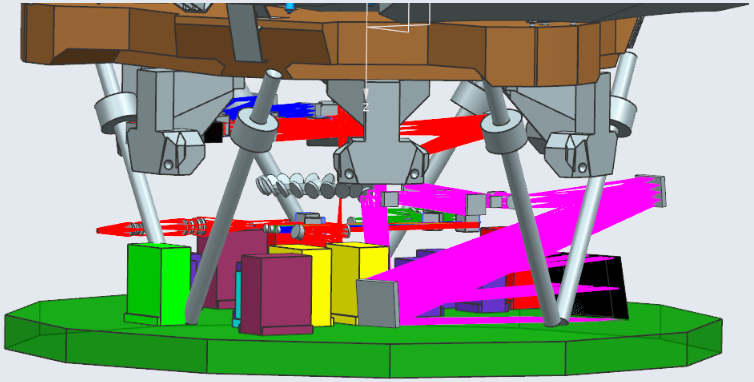


Barrel Deployment

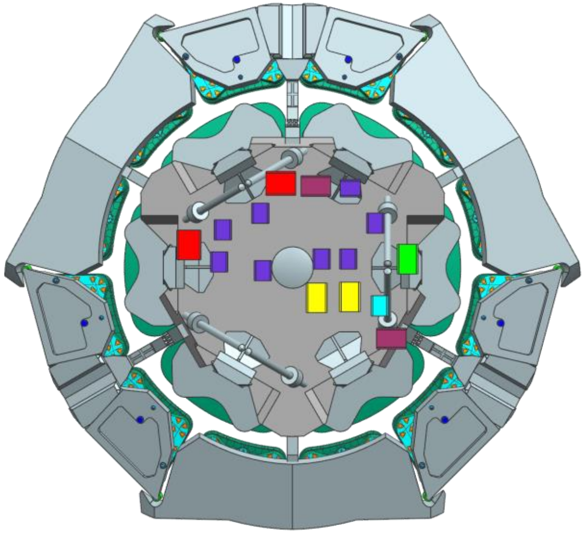


LC6M Payload Packaging

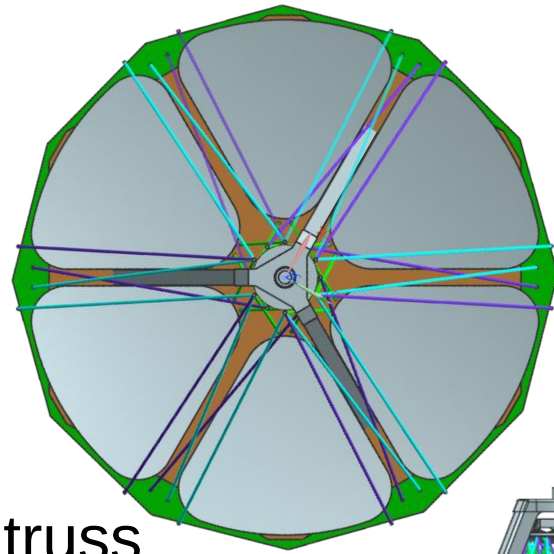


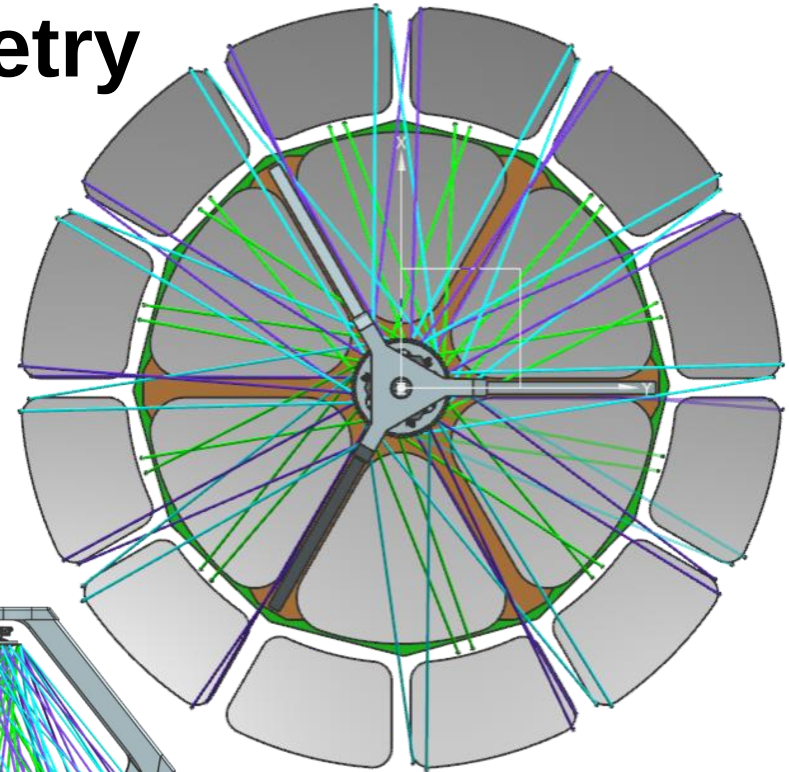


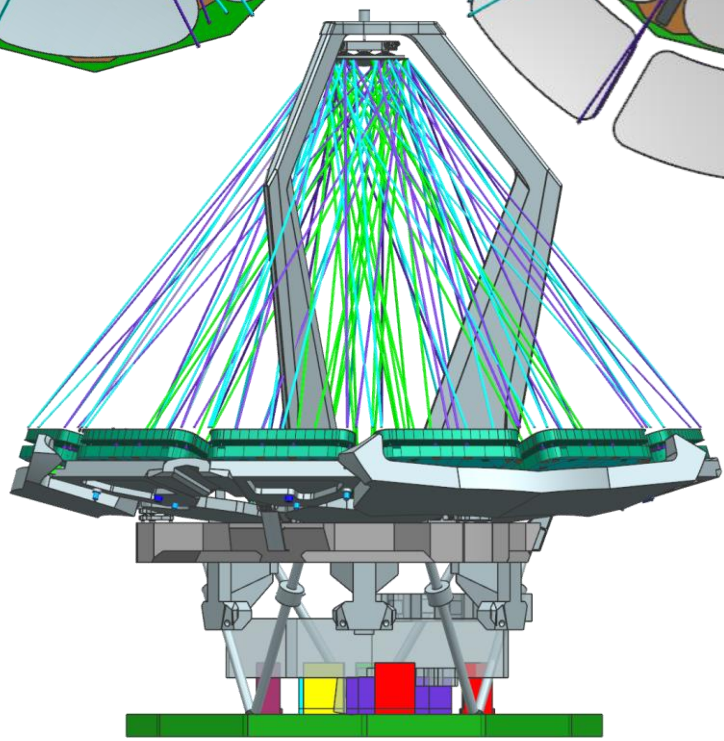
- Instrument and electronics box packaging for the deployable LC6M
  - 2 red boxes for thermal – 12 card 9U type
  - 2 yellow boxes for FCA – 10 card 9U type
  - 1 blue box for deployment/latching – 8 card 6U type
  - 1 green box for RBA – 10 card 9U type
  - 8 purple boxes for instruments – 8 card 6U type
  - 2 brown boxes for metrology – 10 card 9U type
  - Total of electronic boxes: 16



LC6M Laser Truss Geometry





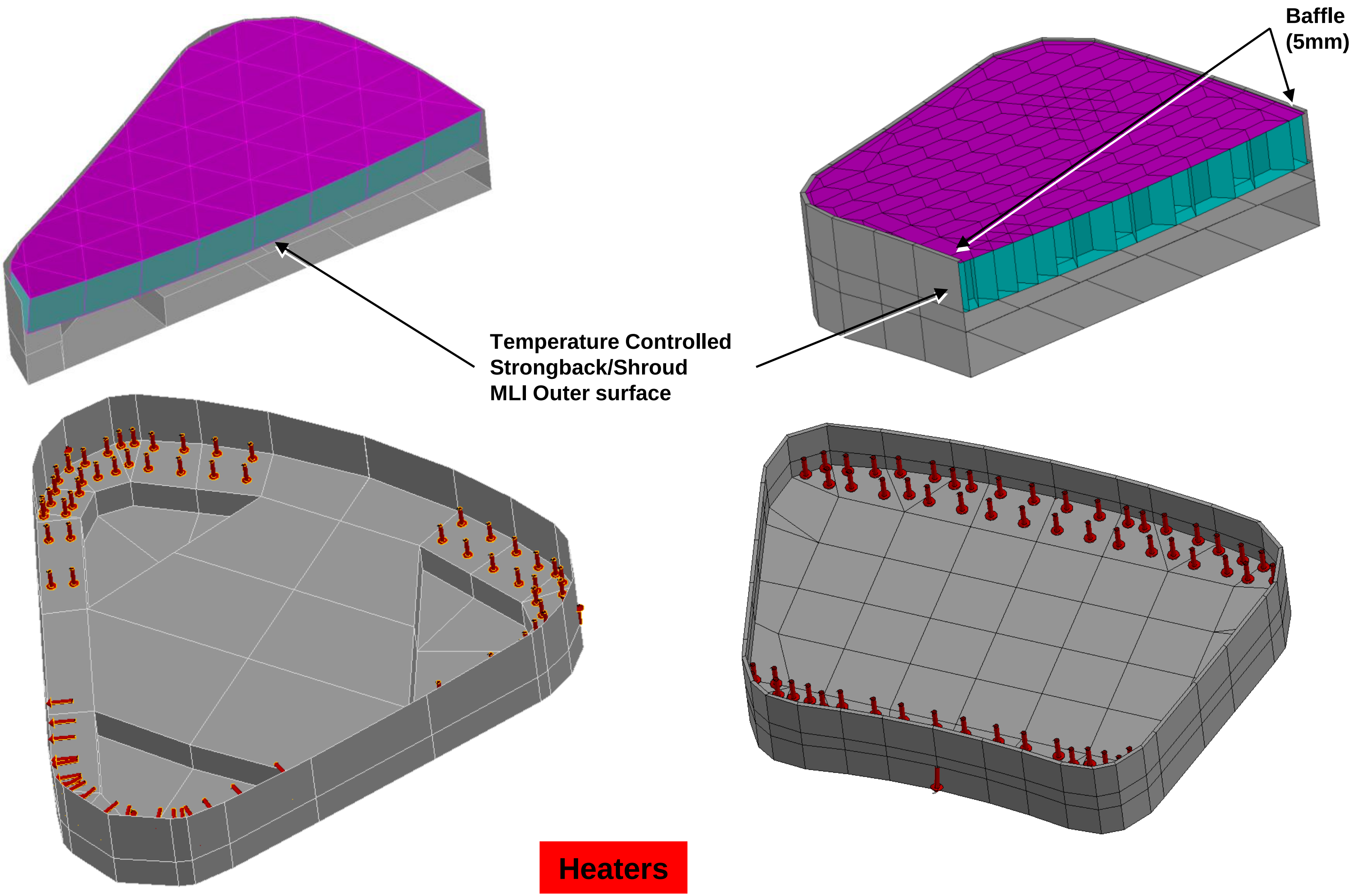


- High stiffness truss configurations for good observability of segment, SM motions
- Laser gauge beams avoid struts

Temperature Controlled Shrouds

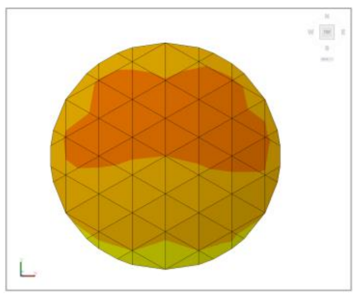
PM Inner Segment

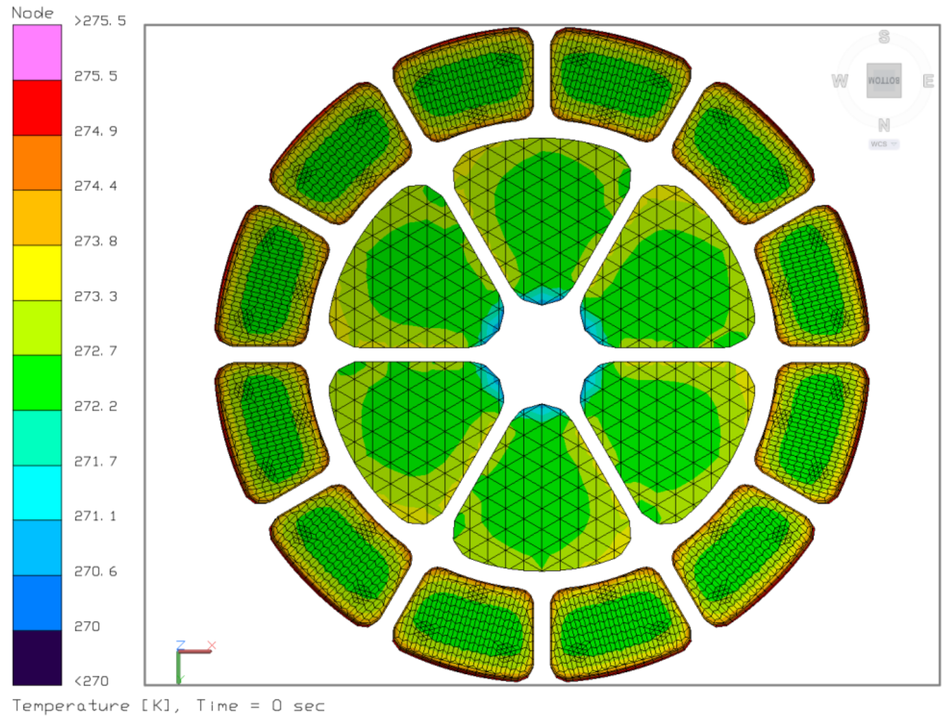
PM Outer Segment



Static Thermal Analysis Results

Component	Power
AMS	191.4
Primary - Inner Segment	233.4
Primary - Outer Segment	372.9
Secondary	12.6
TOTAL	**810.3**





KEY TAKEAWAYS:

1. Minimal drift between cases
2. Minimal radius of curvature change due to bulk temp change
3. ~35W (inner segment) and ~31W (outer segment) needed for PM

Deployed LC6M Preliminary Mass Estimate

Element Name	ASM PARENT	Qty	Material	CBE Mass /Unit (Kg)	CBE MASS (kg)	JPL Uncertainty Factor	CBE Mass+JPL Uncertainty Factor
HABEX SEGMENT TELESCOPE Assembly (6m--18 Segment)	HABEX ASSY	1			**4103.0**	**1.31**	**5387.6**
Primary Mirror ASM	HABEX ASSY	1			1055	1.3	1371.2
Secondary Mirror ASM	HABEX ASSY	1			53	1.3	69.2
High LoRes IR ASM	HABEX ASSY	1			276	1.3	359.3
LoRes IR ASM	HABEX ASSY	1			200	1.3	260.1
Starshade ASM	HABEX ASSY	1			237	1.3	308.6
Electronics Assy	HABEX ASSY	1			160	1.3	208.0
Aft Metering Structure (AMS) Assy	HABEX ASSY	1			456	1.3	592.8
Secondary Support ASM	HABEX ASSY	1			195	1.3	253.5
Barrel Assembly	HABEX ASSY	1			586	1.3	761.7
Radiator Assembly	HABEX ASSY	1			215	1.3	279.5
Telescope to SC Strut ASM	HABEX ASSY	1			142	1.3	184.3
Cabling Assembly	HABEX ASSY	12			268	1.5	402.3
Dust Cover Assembly	HABEX ASSY	1			73	1.3	95.3
Deployment Mechanism Assembly	HABEX ASSY	1			186	1.3	241.8
Spacecraft Bus Assembly					**2050**	**1.30**	**2665**
Launch Vehicle Assembly					**725**	**1.30**	**943**
Launch Dry Mass (inc. LV Interface)					6603		8638
BOL Mass (post Transfer Orbit)					6428		8410

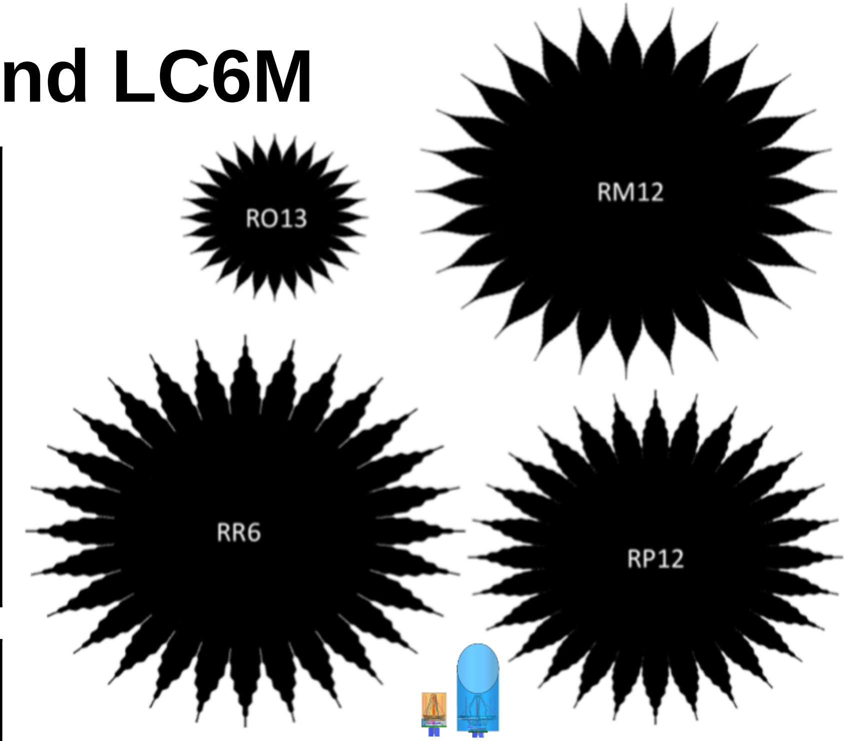
Mass to C3

Atlas V 551	6,100 kg
Delta IV Heavy	9,800 kg
Falcon 9 Heavy	14,000 kg
New Glenn 3	17,000 kg

Starshades for LC4M and LC6M

StarShades for 4 Meter Aperture				
Name	**NL16**	**NO3**	**NQ6**	
Diameter	32 m	64 m	75 m	72m
Petal Length	8 m	16 m	18.75 m	16m
Bandpass	400-500 nm	400-500 nm	400-500 nm	150-500nm
IWA	60 mas	24 mas	20 mas	30mas
Distance	55,004 km	275,020 km	386,750 km	251,519 km
Bandpass	800-1000 nm	800-1000 nm	800-1000 nm	300-1000nm
IWA	120 mas	48 mas	40 mas	60mas
Distance	27,502 km	137,510 km	193,375 km	125,760 km

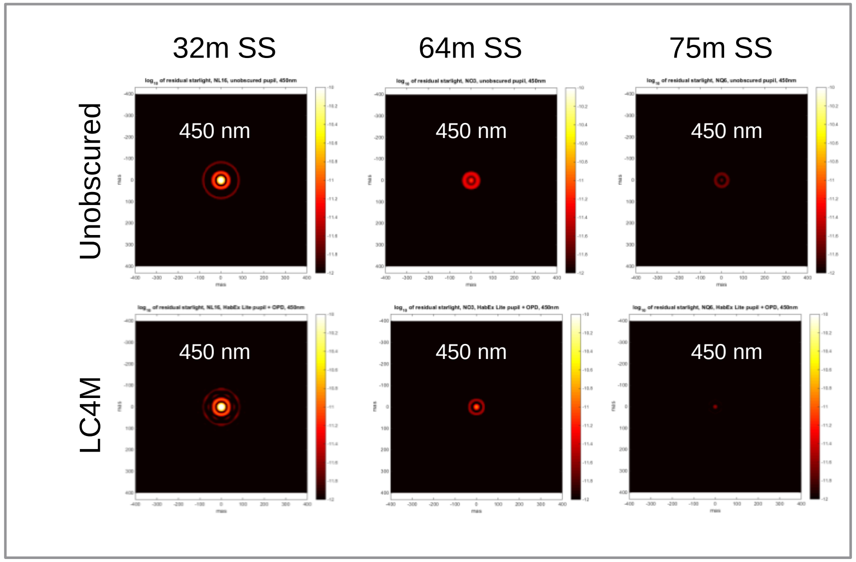
StarShades for 6 Meter Aperture				
Name	**RO13**	**RP12**	**RR6**	**RM12**
Diameter	32m	64m	75m	72m
Petal Length	8m	16m	18.75m	16m
Bandpass	400-500nm	400-500nm	400-500nm	150-500nm
IWA	64mas	27mas	21mas	31mas
Distance	51,570km	244,460km	368,330km	239,540km
Bandpass	800-1000nm	800-1000nm	800-1000nm	300-1000nm
IWA	128mas	54mas	42mas	62mas
Distance	25,785km	122,230km	184,165km	119,770km

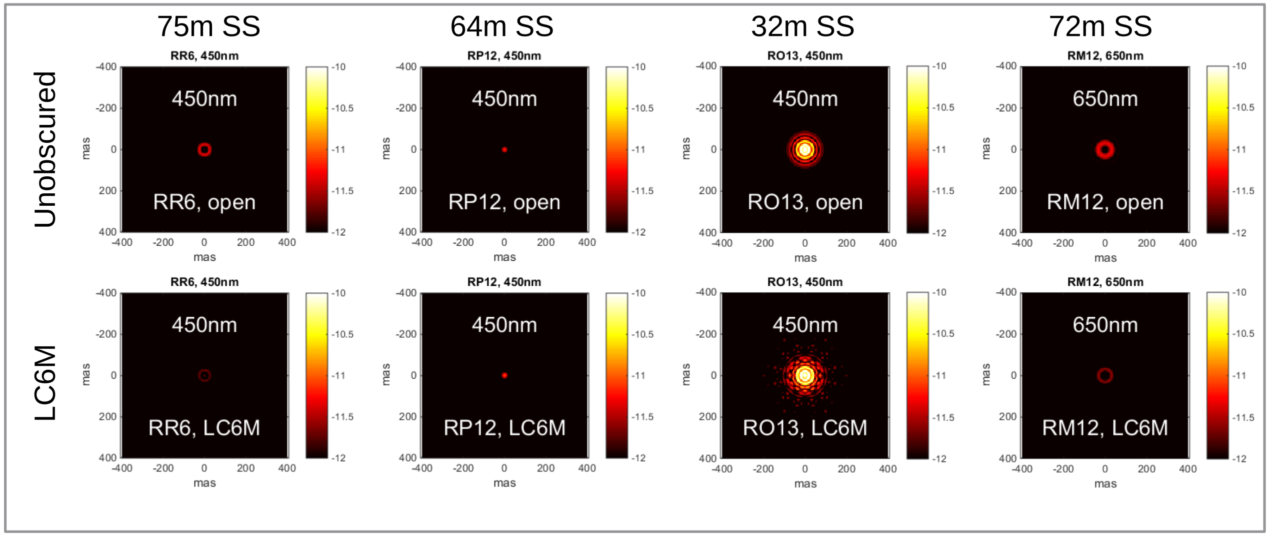


- Large, narrow-band, short-wave starshades provide best IWA
- Large wide-band starshades are best for spectroscopy
- Small narrow-band starshades best for search, orbits
- Combination has the best exoEarth yield

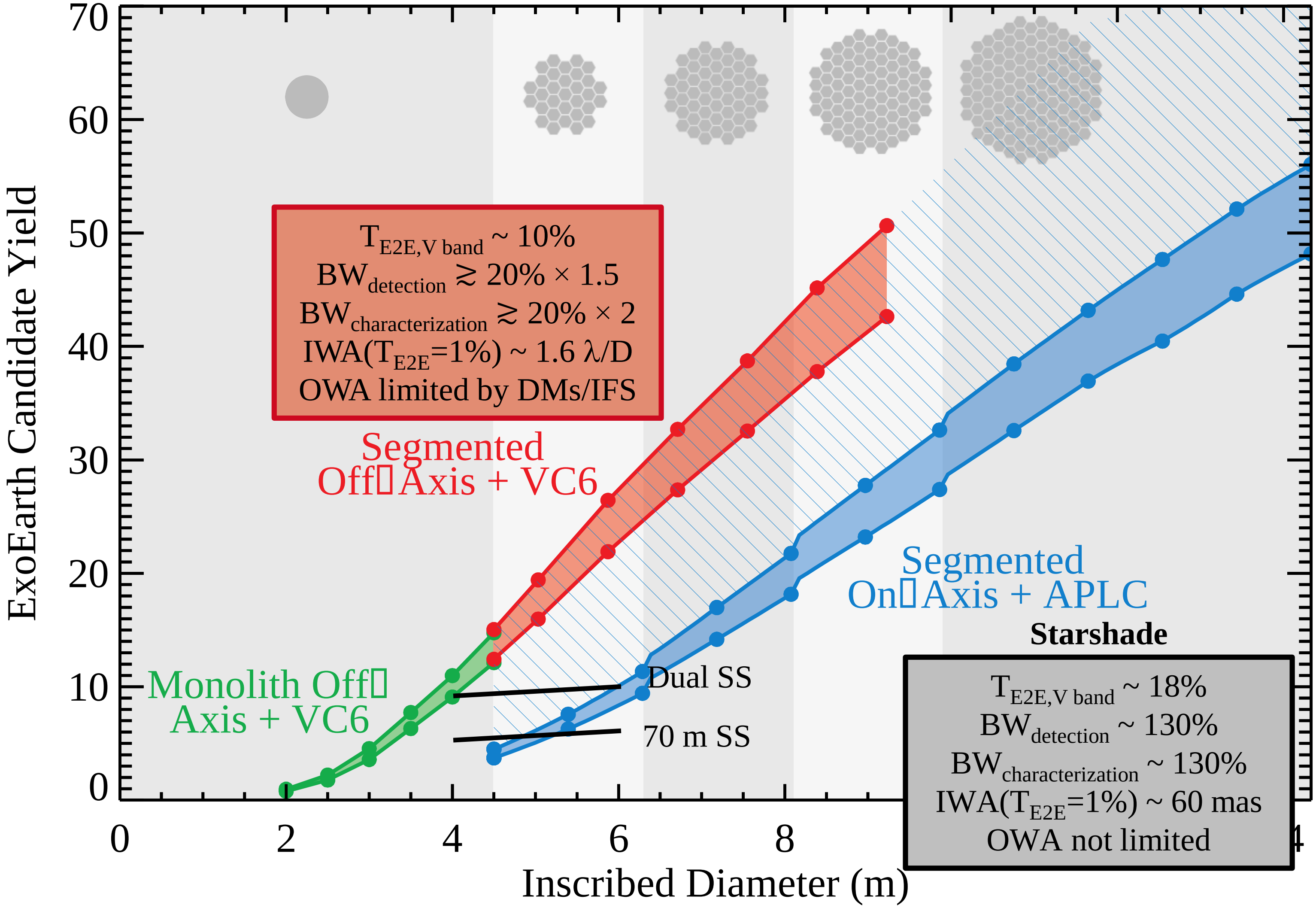
Starshade Performance Not Impaired By Segmentation

- Segmented aperture contrast is essentially the same as for a same-size unobscured aperture
  - LC4M and LC6M





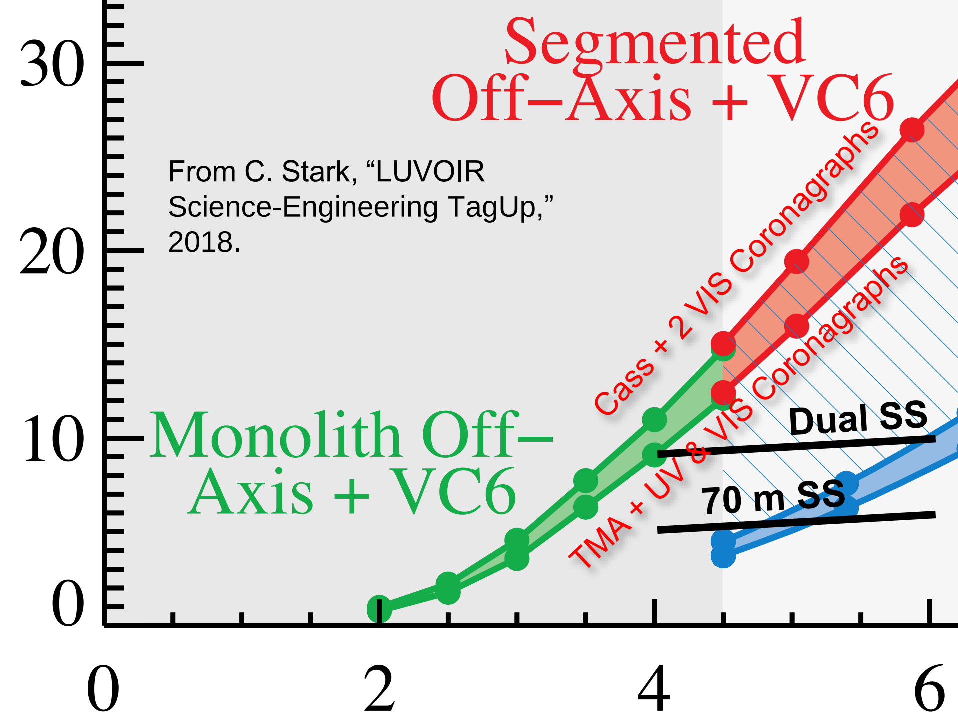
Segmented Coronagraph ExoEarth Yield



- From C. Stark, "LUVOIR Science-Engineering TagUp," 2018.

Yield for D ~ 4 m

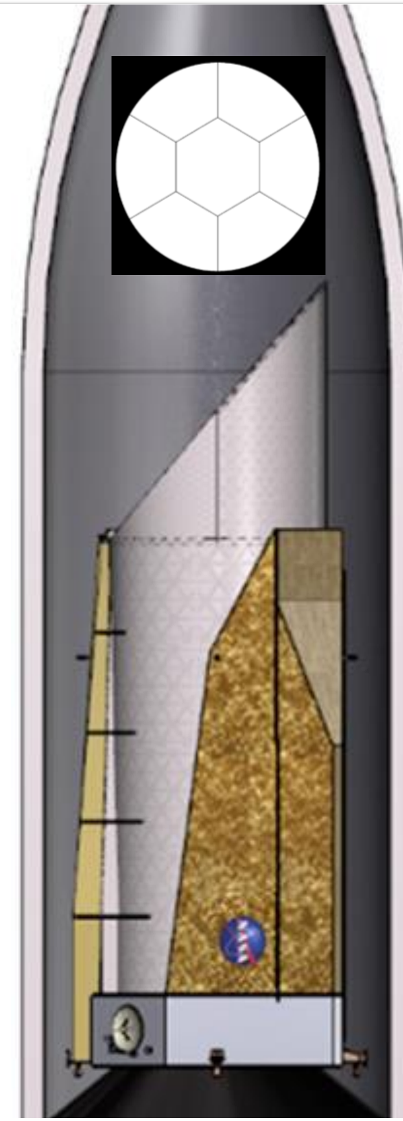
- Coronagraph yield ~9 (TMA) to ~12 (Cass telescope)
- Assumes no penalty for segmentation
- Assumes coronagraphs operate 2 channels in parallel



- Assumes optimized orbital phase for spectral characterization
- A Coronagraph-equipped TMA telescope TMA+Coro ~ Dual SS
- Coronagraphs and starshades do not yield the same spectra:
  - Starshades achieve higher quality spectra, but are limited to 1 visit
  - Coronagraphs perform spectral characterization in a tiered manner over multiple visits

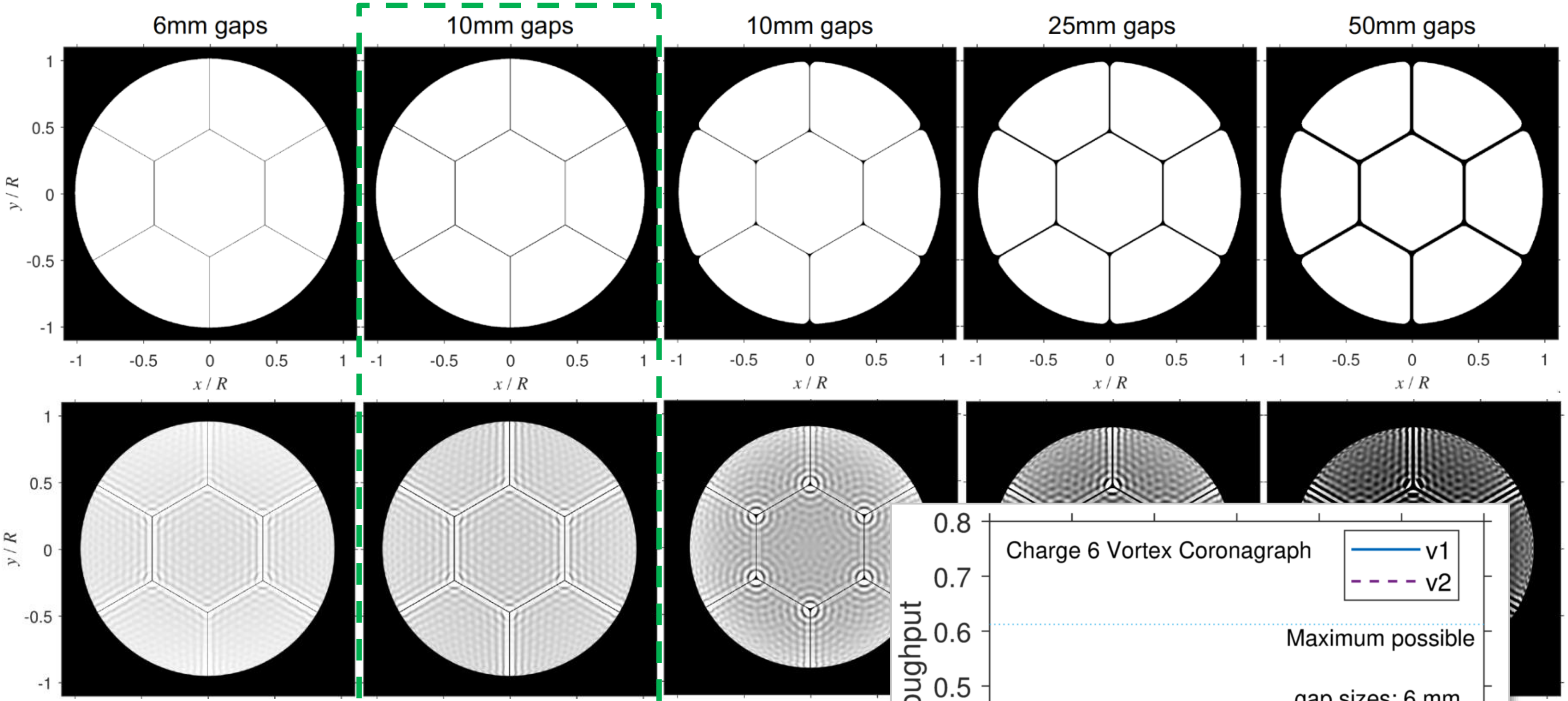
Segmented Off-Axis HabEx

- Quick look at a segmented primary mirror for Baseline HabEx
- Coronagraph performance
- Ultra-stability
  - Thermal control
  - Active phasing
- Mass and Power

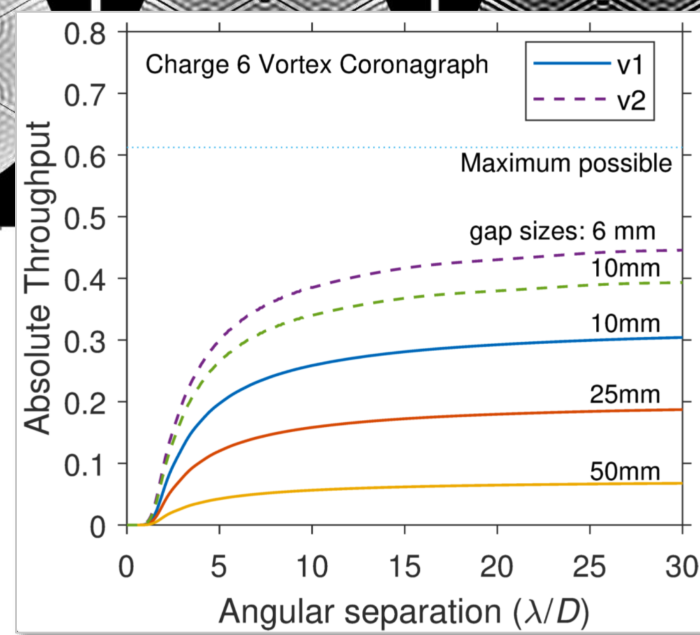


<u>HabEx4seg:</u>
Coronagraph-compatible segmented aperture, Non-deployed OTA, SLS

Coronagraphy With a Segmented Aperture



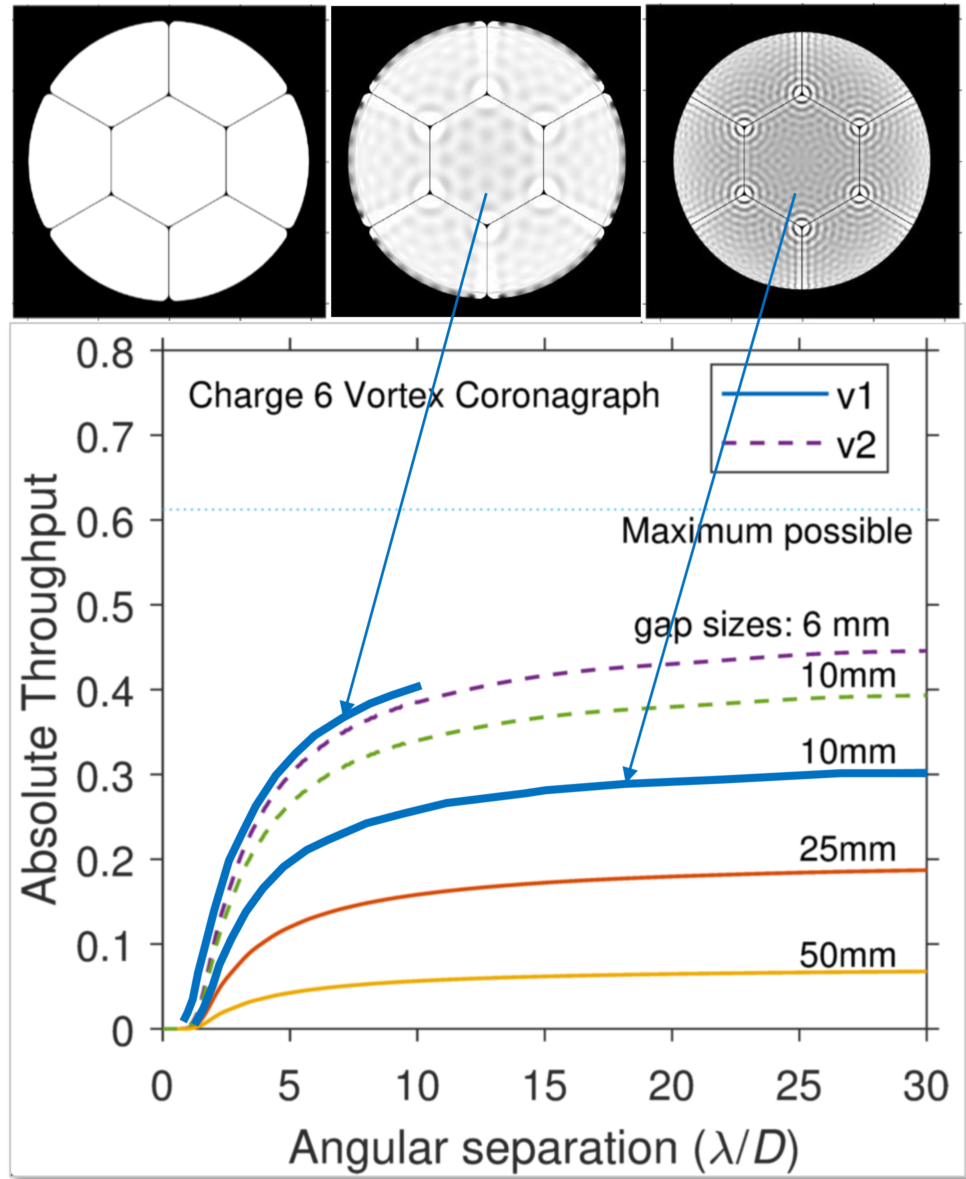
From G. Ruane, J. Jewell, A.J. Riggs, “Apodized vortex coronagraphs for off-axis segmented telescopes,” 2018.



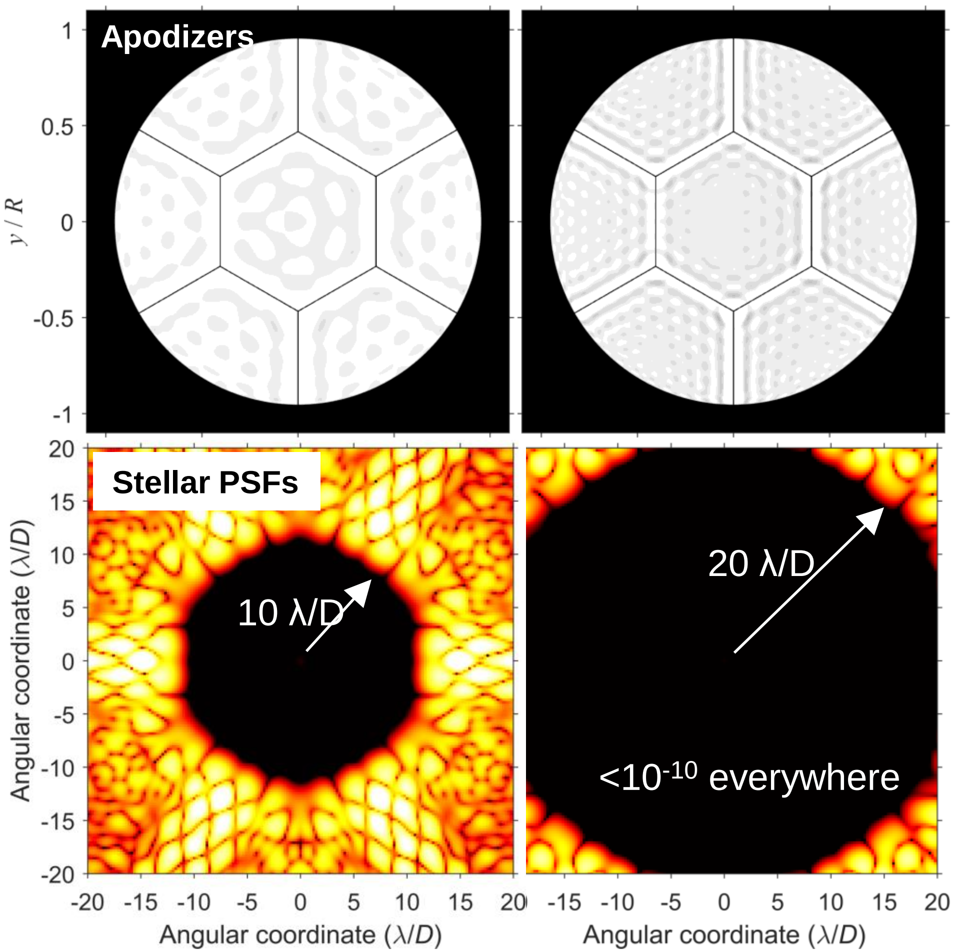
- Off-axis, 4-m HabEx segmentation, with corresponding AVVC6 apodization masks show impact of gap size and round corners

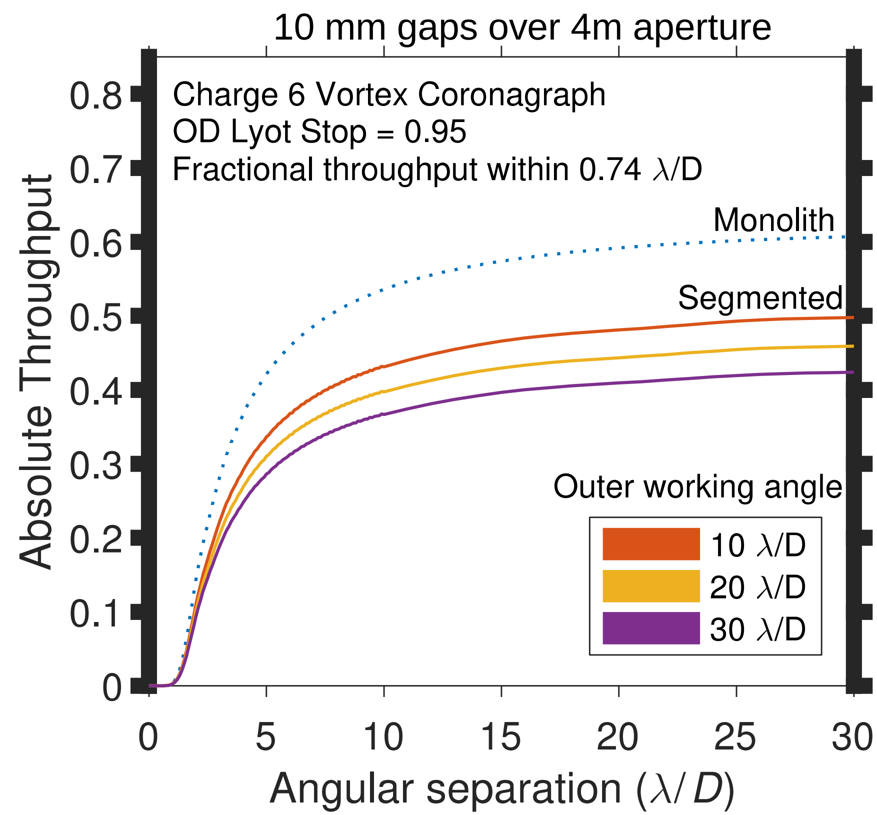
Tuning Vector Vortex Apodization

- Off-axis, 4-m (or larger) HabEx segmentation
- AVVC6 apodization masks can be tuned to particular observing requirements
- This compares designs for the case of 10 mm gas with rounded corners
- Tuning for a 2-10 λ/D dark hole gives higher throughput in that region
- Work continues for Vector Vortex coronagraphs
  - Phase-only compensation, using DMs
  - Hybrid approaches
  - Increase D to improve performance



Trade-off between outer working angle and throughput

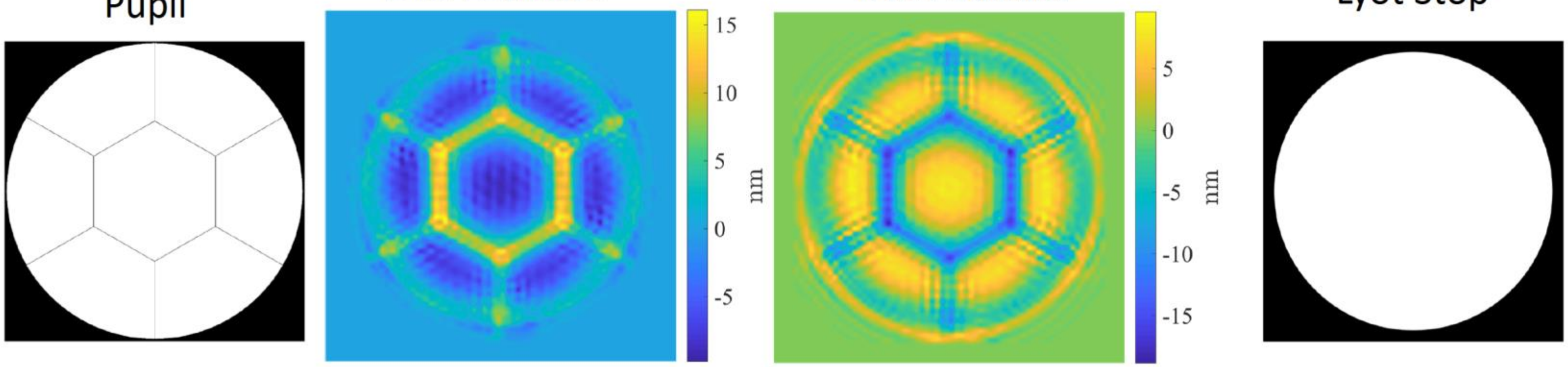




Deformable Mirror Vortex Coronagraph (DMVC)

Jet Propulsion Laboratory
California Institute of Technology

DMVC Design

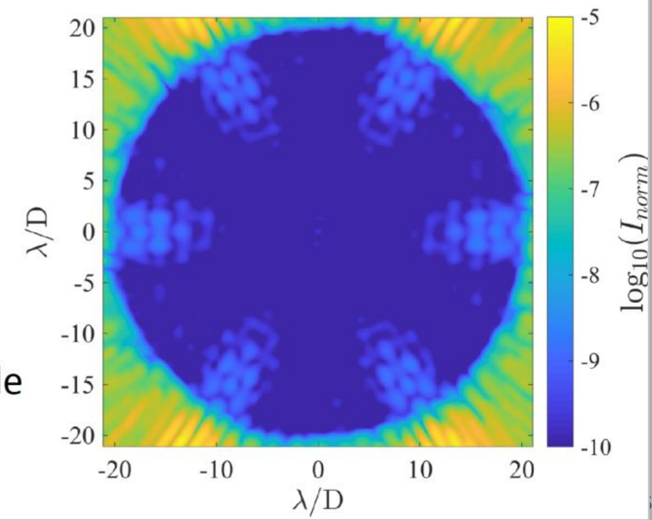


From A.J. Riggs, G. Ruane, “Deformable Mirror Vortex Coronagraphs (DMVCs) for an Off-Axis, Segmented HabEx Architecture,” 2018.

- 6mm gaps
- Lyot stop: OD = 95% D, no obscurations
- 20% spectral bandwidth centered at 500nm
- 2 DMs with 64x64 actuators
- OWA = 20 λ_0/D (reduced to mitigate segment diffraction)

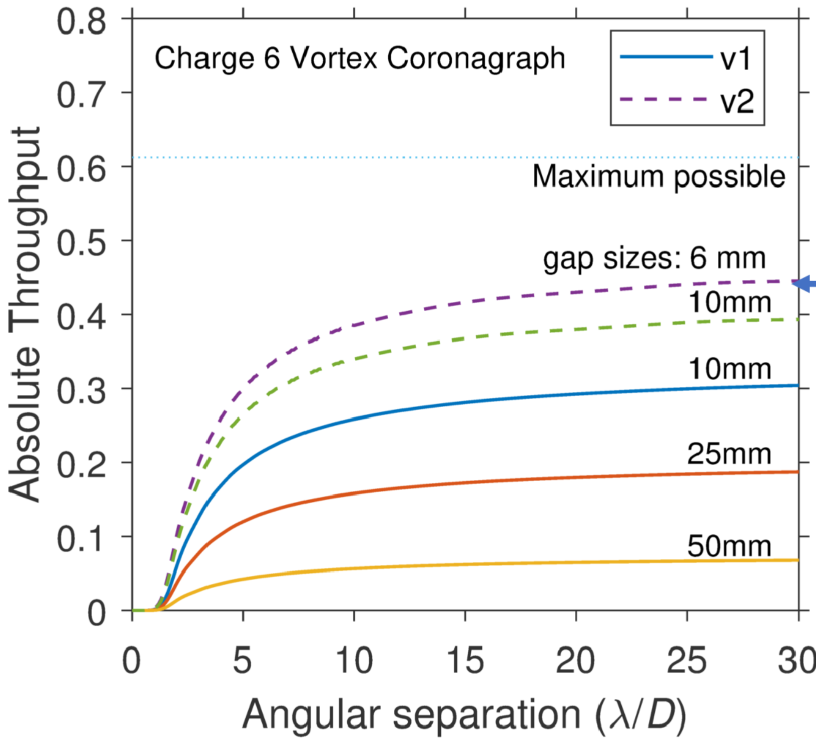
- 2×10^{-10} mean normalized intensity over entire dark hole
- $< 10^{-10}$ normalized intensity from 2-10 λ_0/D

Stellar PSF

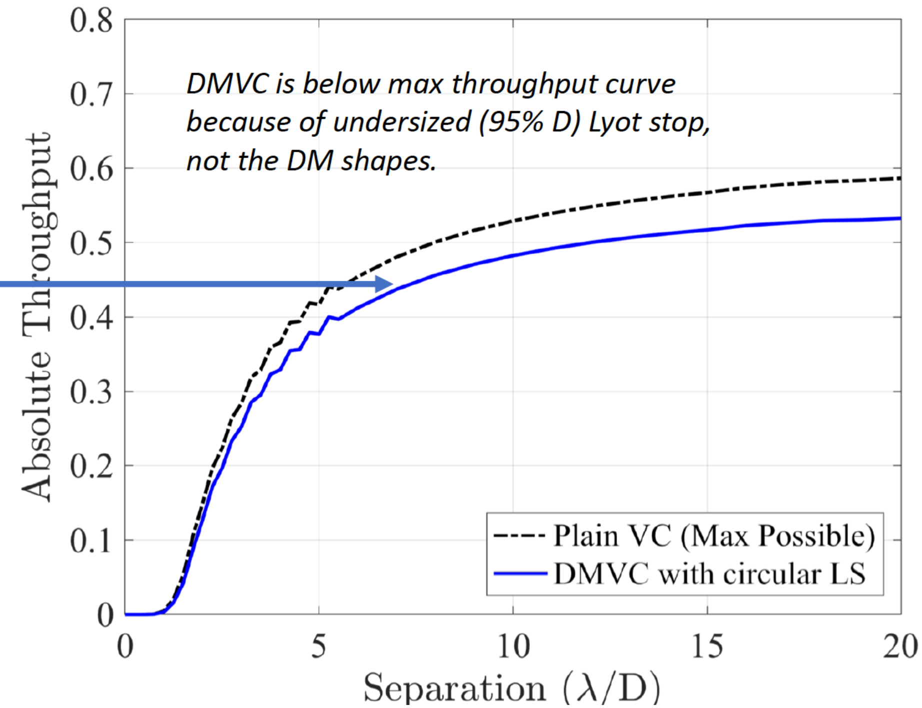


Comparing AVVC and DMVC Throughput

Apodized Vortex Results
by Garreth Ruane



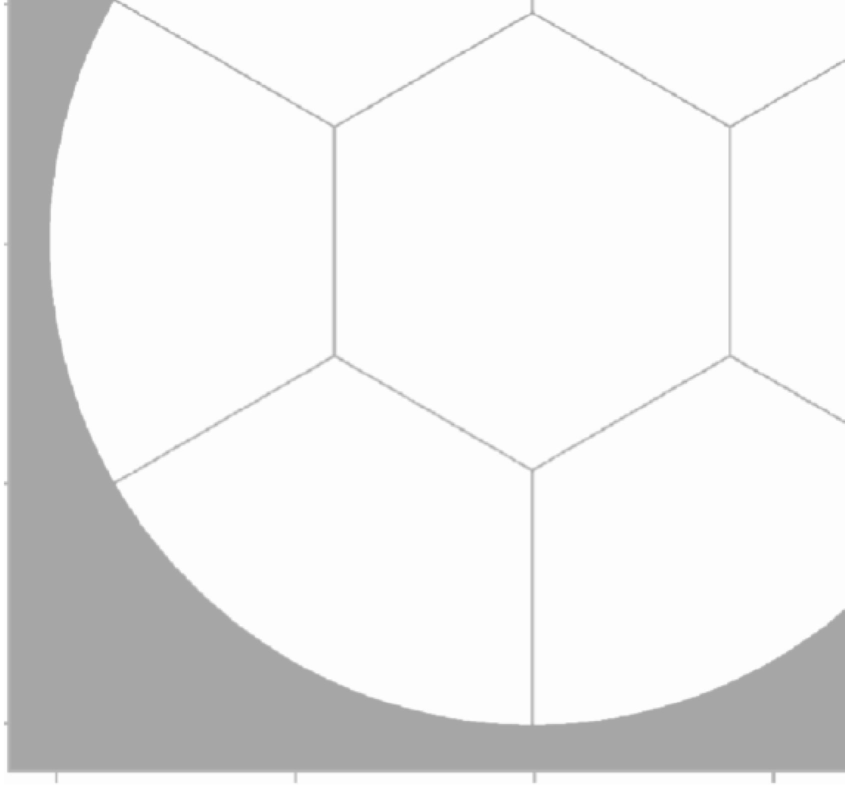
Deformable Mirror Vortex Coronagraph



From A.J. Riggs, G. Ruane, “Deformable Mirror Vortex Coronagraphs for an Off-Axis, Segmented HabEx Architecture,” 2018.

- DMVC provides higher throughput than AVC, for 6 mm gaps at least
- DMVC is easier to align – and DMs are needed for aberration correction anyways
- AVC has better (larger) OWA
- Combination...?

Implementing 10 mm Gaps



- PM segment driving requirements:
  - <10 nm RMS figure error
  - 10 mm gaps
    - Polish to edge of clear aperture
  - 5 mm radius corners
  - 3DOF RB actuation only
  - SFAs as needed
- Localized thermal control
  - Thermal “bathtub” provides high stability
- Metrology (Laser Truss, Edge Sensors, or both):
  - Indent core in region of beam launcher or edge sensor
  - Point beam launchers through gap at SM corner cubes

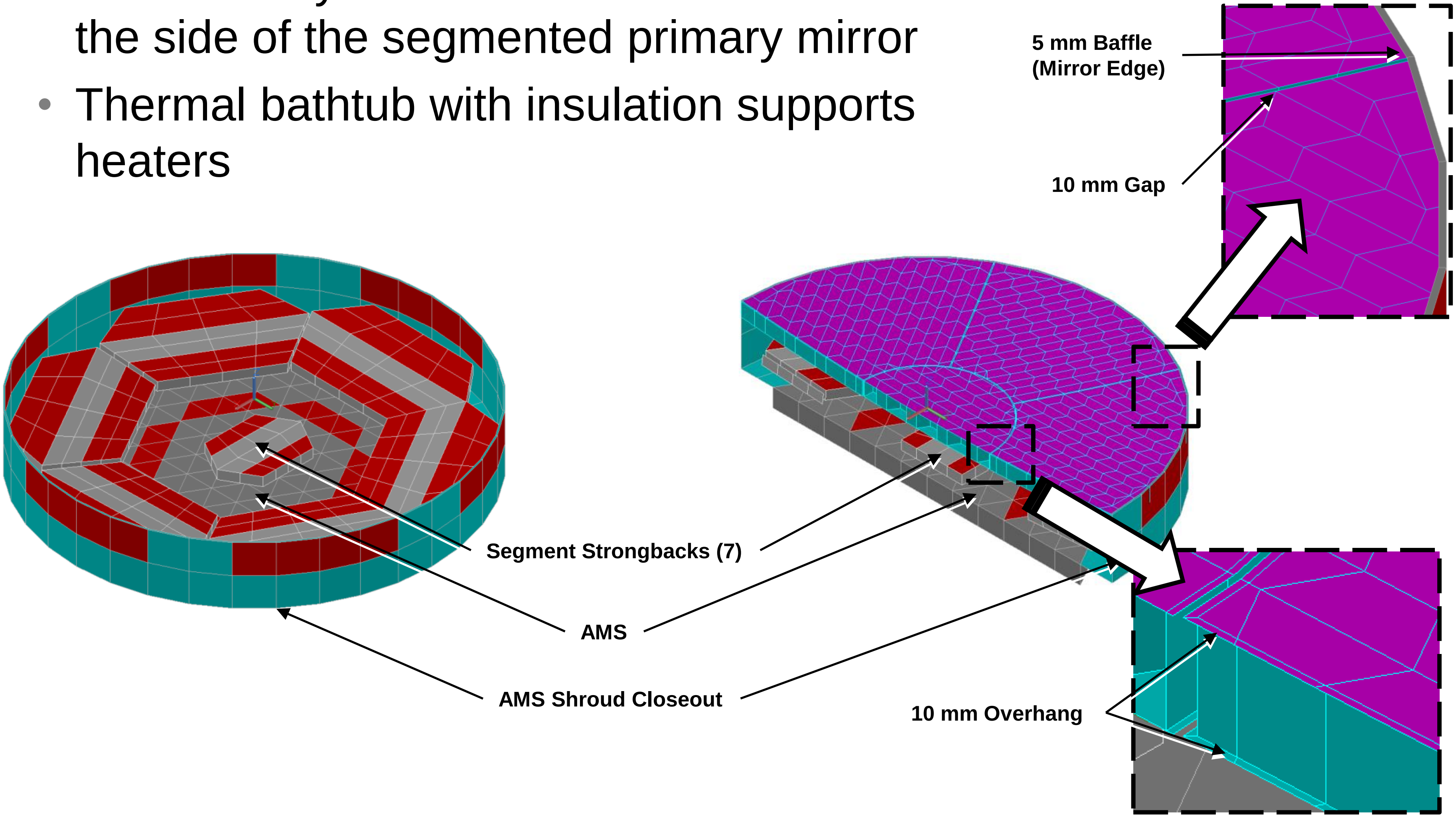
Segmentation Provides Lower Mass Option

Off-Axis HabEx Primary Mirror Mass Comparison					
CBE Mass in kg	4 m Monolith	4 m Segmented: 7 Segments		4.5 m Segmented: 7 Segments	
Actuation	None	RBAs only (6DOF)	SFAs & RBAs (3DOF)	RBAs only (6DOF)	SFAs & RBAs (3DOF)
Mirror Substrate Mass	1,356	207	207	291	291
Mirror Support Structure Mass	?	194	194	276	276
Mid-Body/Reaction Structure Mass	N/A	57	57	73	73
Bond Pads + Flexures	?	55	55	55	55
Thermal Control System Mass	?	21	26	21	26
Surface Figure Actuator Mass	N/A	0	28	0	28
Rigid Body Actuator Mass	N/A	44	22	44	22
Electronics Mass	?	9	23	9	23
Cabling Mass	?	5	13	5	13
Metrology Mass	?	6	6	6	6
Mirror Substrate First F-F Mode freq	64 Hz	280 Hz	280 Hz	210 Hz	210 Hz
Total Mirror System Mass	1,356	597	631	779	813
Total Mirror System Stiffness	?	?	?	?	?

- Segments are considerably lighter than a monolith
  - Ripple effect will substantially lower overall telescope mass

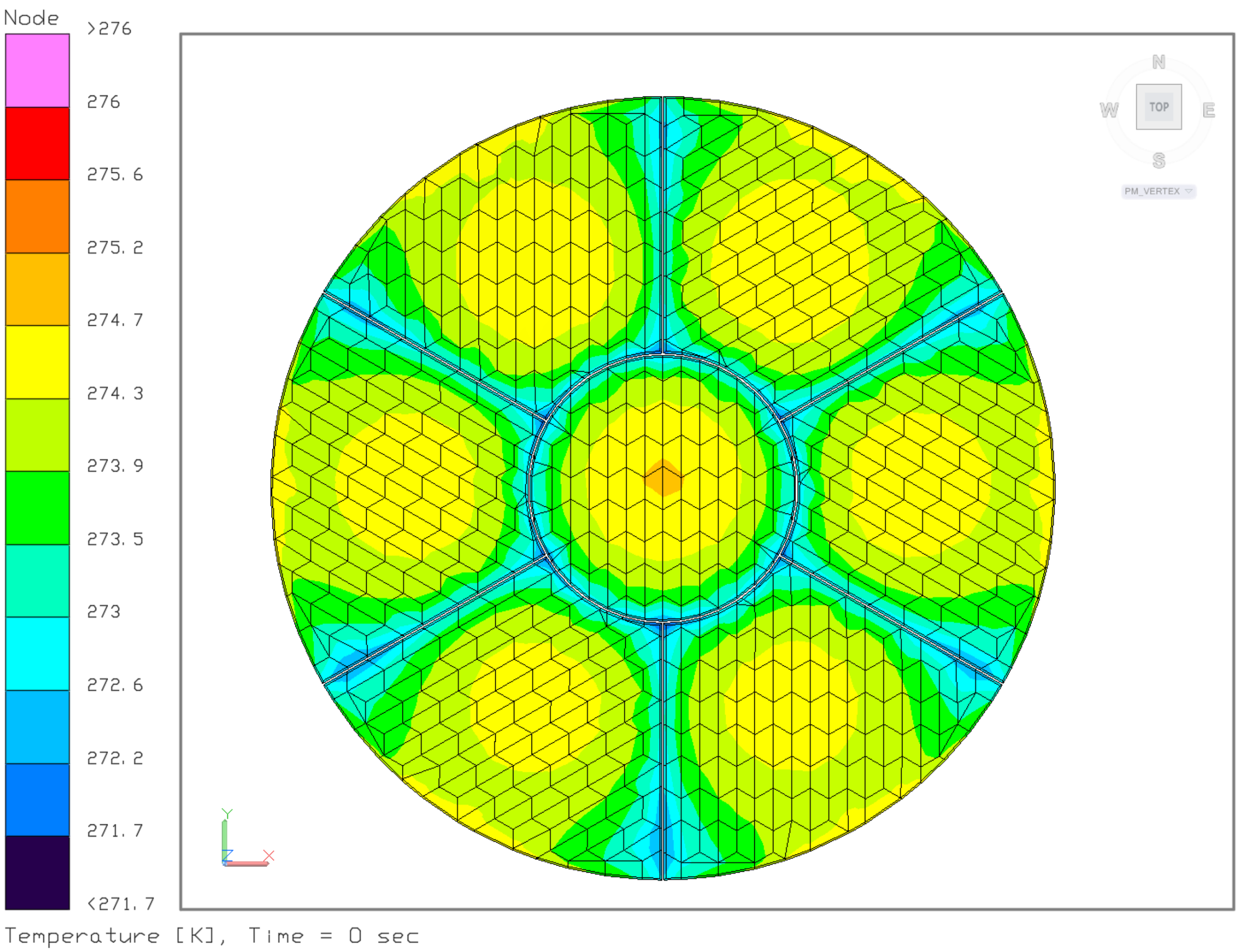
Thermal Design

- No baffle tube heaters, no closable cover
- Heaters only on structures behind and on the side of the segmented primary mirror
- Thermal bathtub with insulation supports heaters



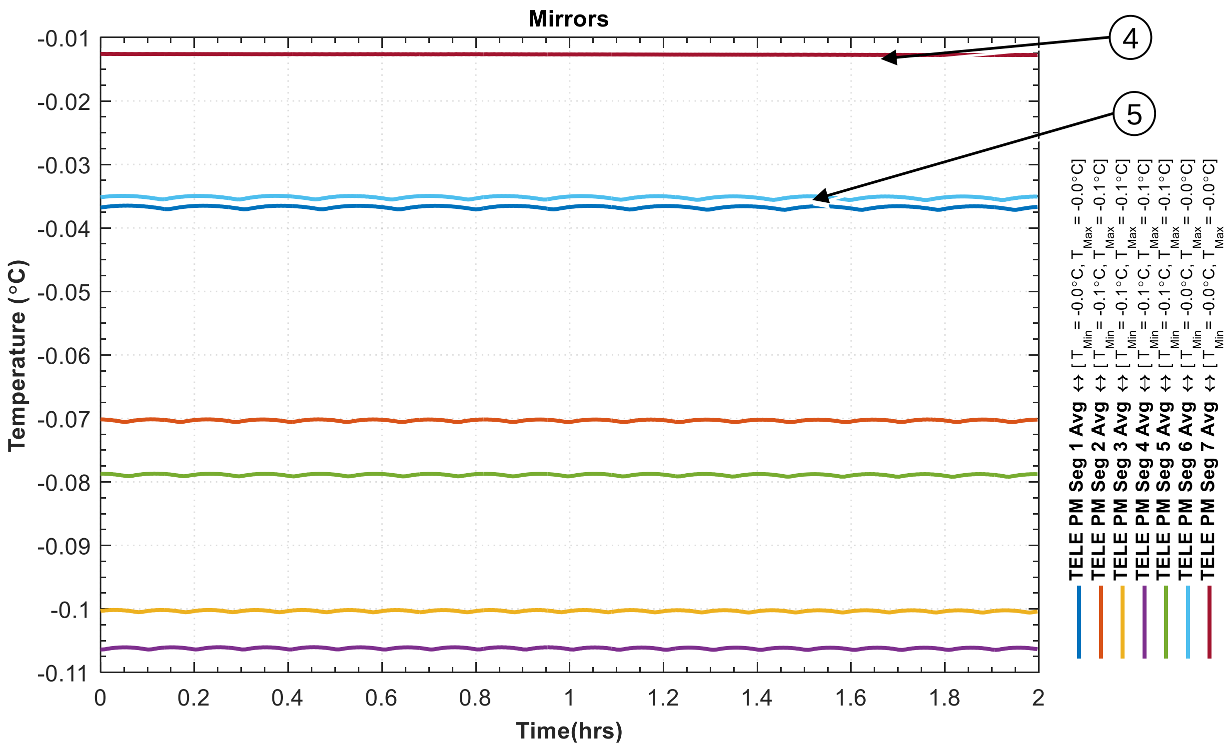
Static Temperature Performance

- Static temperature distribution in L2 orbit
  - Reference temperature is 0C
- Small thermal deformations will likely be fully “correctable” by speckle nulling control
  - OTA active mirrors
  - Coronagraph DMs



Drift Temperature Performance

Optic[1]	Material	Thru[2] Thickness Drift(K)	Thickness (m)	Radius of Mirror (m)	CTE (ppm/K)	RMS SFE[3] (pm)
Segment	Glass	0.001	0.15	0.69	0.015	7
		0.0100				68
		0.050				340
Monolith	Glass	0.001	0.47	2.04	0.015	19
		0.010				191
		0.050				957



Notes:

1. This table estimates the temperature control needed of each optic for both a monolith and segmented primary mirror.
2. Allowable temperature drift of the mirror.
3. RMS SFE estimate is based on temperature drift of a circular optic. The same temperature drift equates to 3x more SFE in the monolithic mirror due to the larger mirror diameter. RMS WFE is twice the RMS SFE.
4. The inner segment temperature drift is less due to a smaller inner strongback giving more view to the AMS.
5. At L2, there is minimal temperature drift. The temperature drift of the segments is caused by the heater bang (on)/bang (off) control algorithm. The heater dead band on the strong back and AMS is 0.1K. This equates to a 1 mK temp drift on the outer segments.

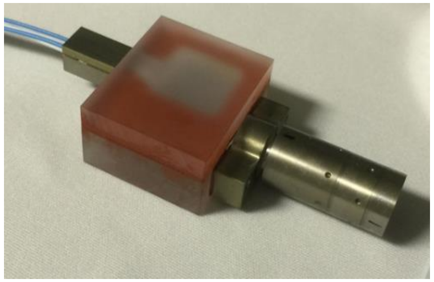
Localized Thermal Control Reduces Power

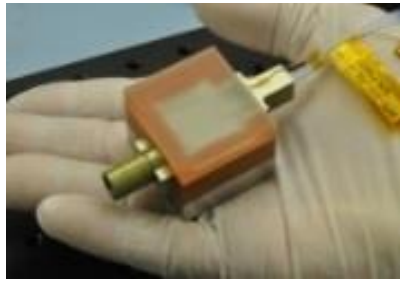
Off-Axis HabEx Thermal and Power Comparison					
	4 m Zerodur Monolith	4 m Segmented: 7 Segments		4.5 m Segmented: 7 Segments	
Actuation	None	RBAs only (6DOF)	SFAs & RBAs (3DOF)	RBAs only (6DOF)	SFAs & RBAs (3DOF)
Primary mirror heaters (W)	235	260	260	330	330
Inner baffle heaters (W)	2120	0	0	0	0
PM Temperature stability (mK)	0.3	1	1	1	1
Solar array area (m2) *PM HTRS ONLY*	9.3	1.0	1.0	1.3	1.3
Radiator area (m2)	4.2 @ 20C 2.7 @ -80C	4.2 @ 20C 2.7 @ -80C	4.2 @ 20C 2.7 @ -80C	4.2 @ 20C 2.7 @ -80C	4.2 @ 20C 2.7 @ -80C
Thermal system mass (kg)	?	21	26	21	26

- Approach:
  - Thermal “bathtub” stabilizes segment figure to 10s of pm
  - pm Metrology maintains alignments to 10s of pm
- Large savings in power and solar array area
  - 260 W vs. 2355 W for baffle heating approach
  - 1 m^2 vs 9.3 m^2 SA area

Picometer Metrology for Coronagraphy

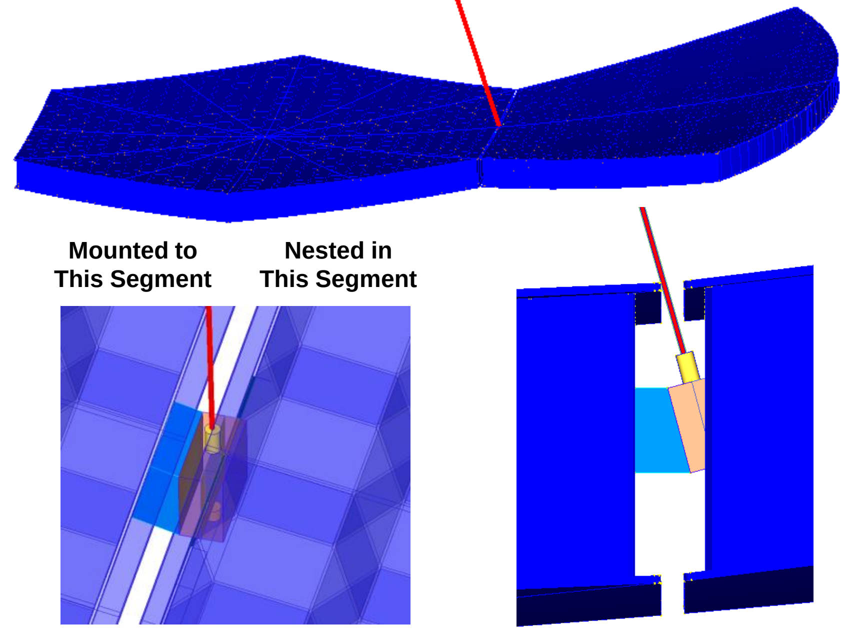
Planar Lightwave Circuit beam launcher





- Current Nanometer-precision Laser MET
  - Heterodyne distance gauges
  - Precision < 1 nm (5 uW)
  - BW 1-5 kHz
- Moving to picometers: current activities
  - Adopt LISA Pathfinder phasemeter electronics
    - Flight-proven pm accuracy
  - Ultra-stable beam launcher

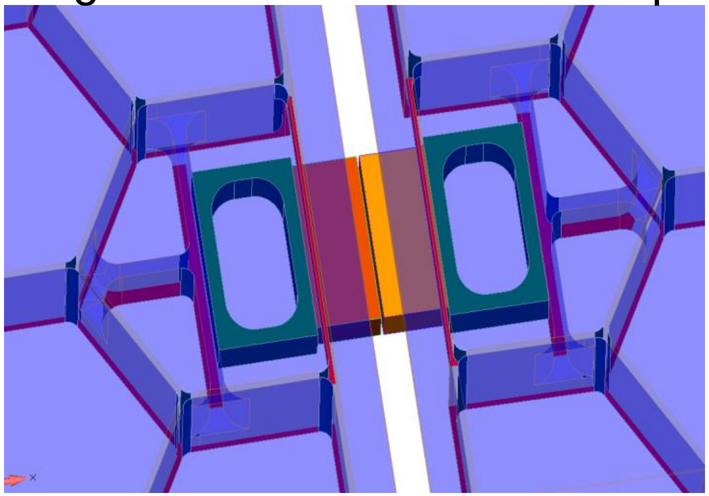
Preserving 10 mm segment gaps



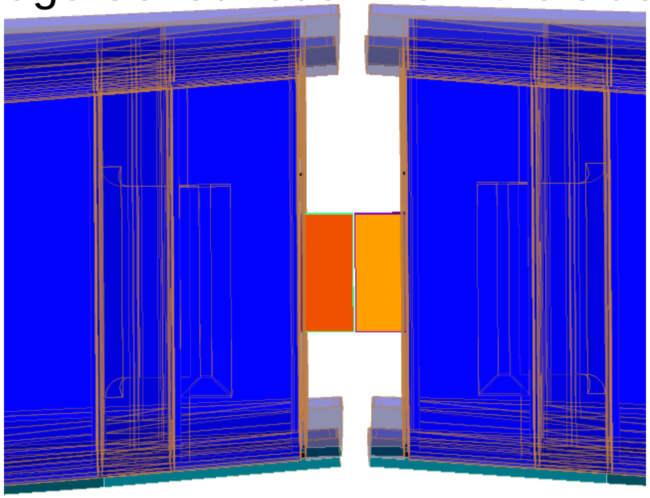
- Segment gaps of 10 cm require
  - Embedded MET beam launchers or Edge Sensors
  - High quality edge figure
  - 3DOF (only) RB actuation
  - Surface Figure actuation

Edge Sensors for Coronagraphy

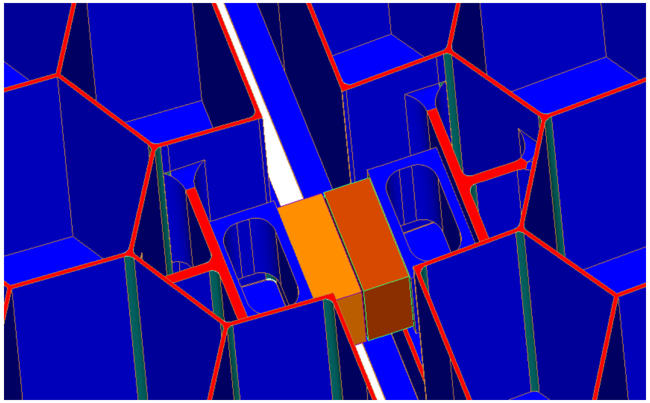
Edge Sensor seen from the top



Edge Sensor seen from the side



Edge Sensor seen from below



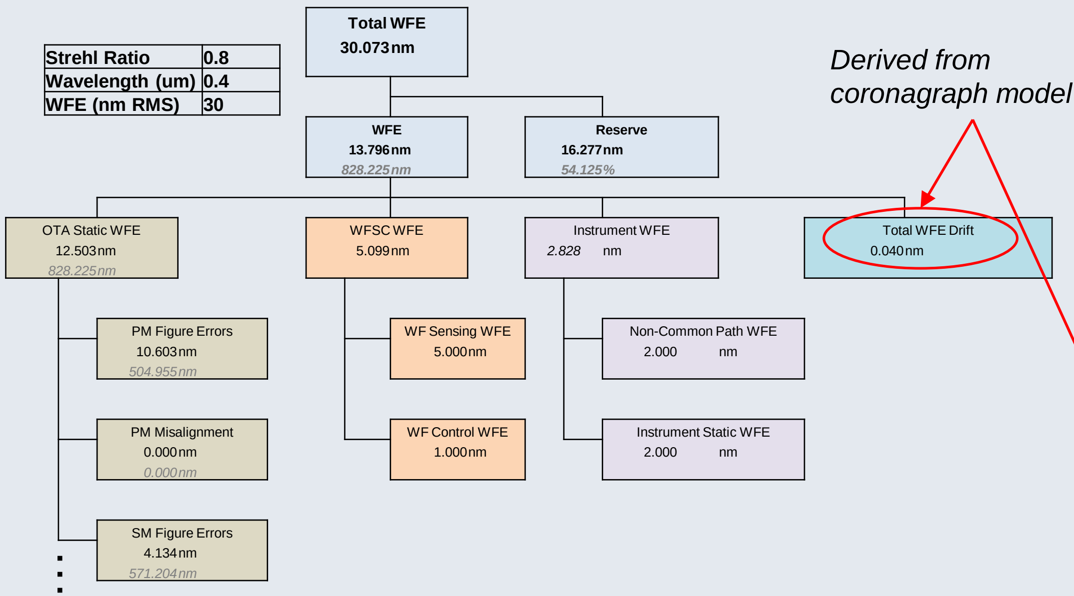
- Sketches show a TMT-style capacitive Edge Sensor
  - Accuracy dependent on gap dimensions and stability
- Other designs may be required for pm accuracy
  - Keck-style interleaved sensors

Discussion

- LC4M is likely the lowest cost telescope capable of providing threshold HabEx exoplanet science
  - With two SS (36 and 72m), yield nearly equals Coro+SS
- LC6M increases D to 6m, but does not significantly increase yield, unless larger SS are provided
  - Deployment brings more complications and risk
- LC6Mnd provides a non-deployed telescope and baffle, lowering risk, but requires an as-yet unproven launch vehicle
  - Preferred if 6m aperture is required
- HabEx4seg, replacing the monolithic PM in the off-axis baseline design, brings coronagraph performance at a lower mass (and cost) design point, with some more complexity
  - Expandable to larger D, with an increase in yield

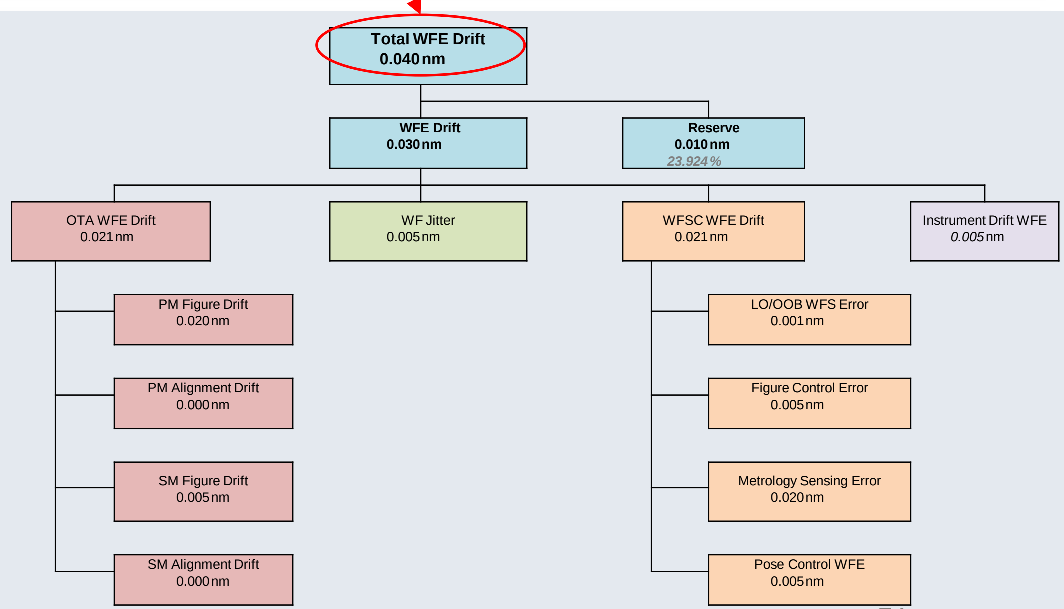
Backup

Notional Error Budgets: UVOIR

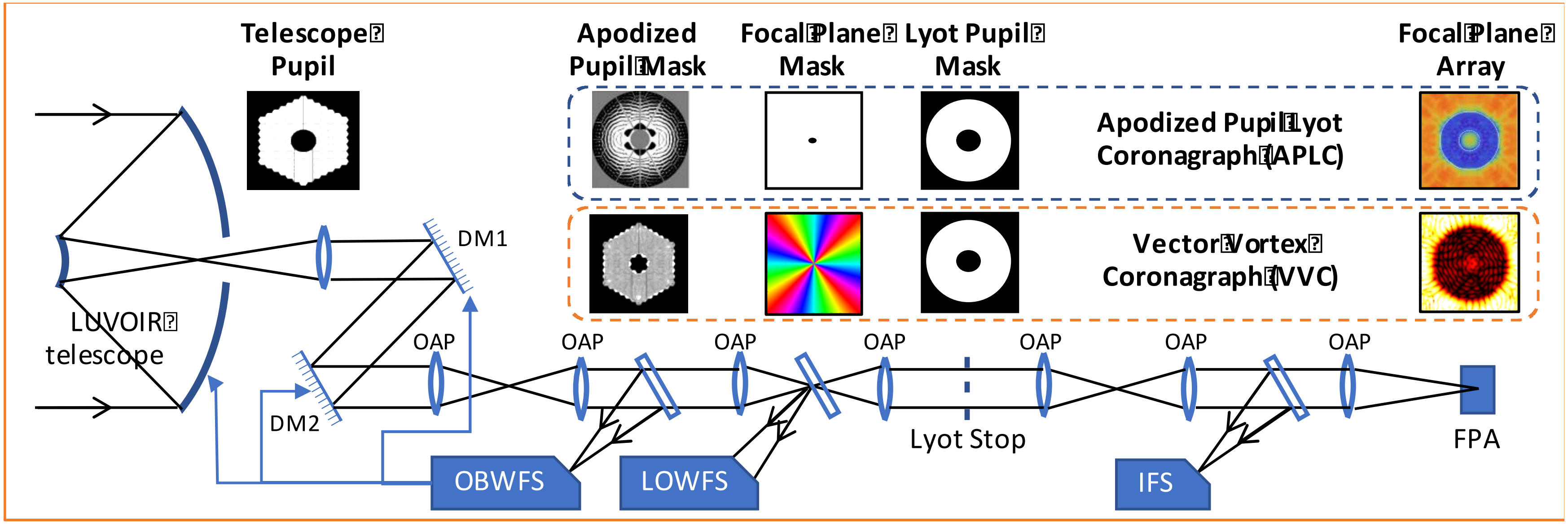


- Total Static WFE for a HabEx or LUVOIR is ~30 nm RMS
  - After initial WFSC
  - During all observations
  - With maintenance controls

- Ultra-stability needed to preserve coronagraphic contrast is ~40 pm RMS
  - During coronagraph observations
- "Normal UV stability" for other observations...
  - ~10 nm RMS

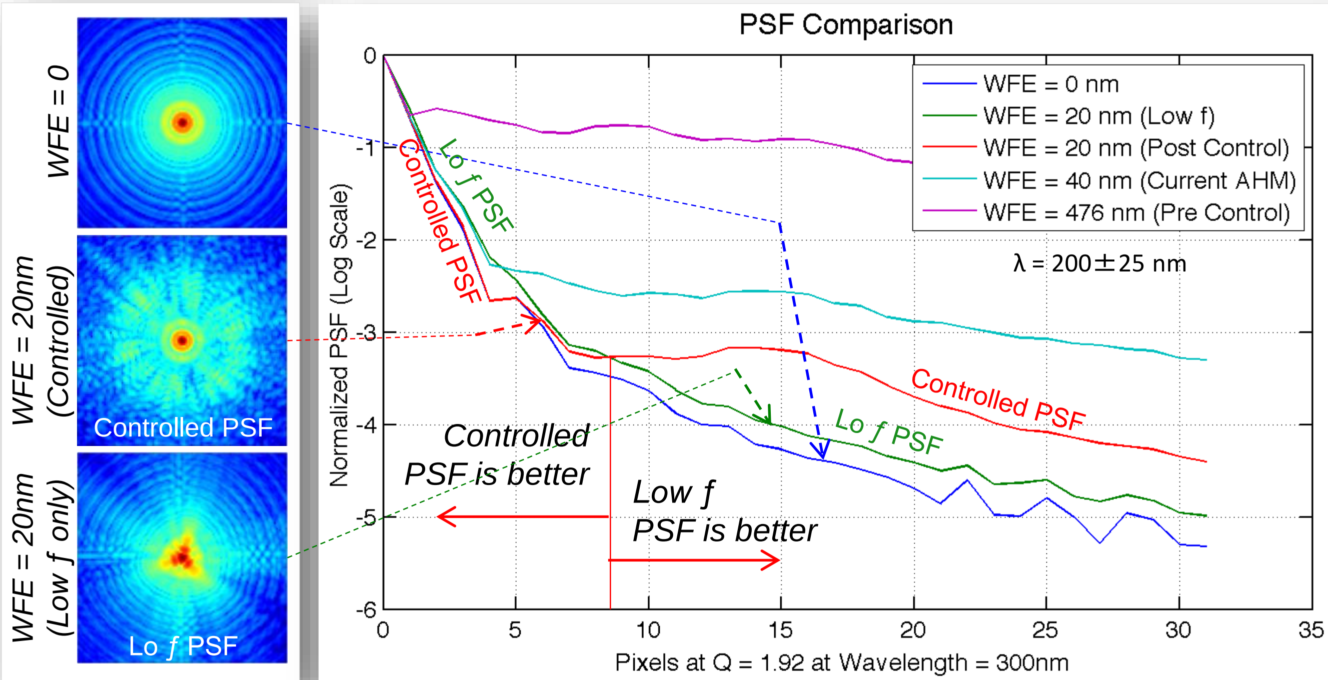


Coronagraphs Need Ultra-Stability



- Coronagraph operation begins with speckle-nulling control (EFC, e.g.)
  - Establish high contrast dark hole at the science FPA: 10^{-10} over 3-10 λ/D, e.g.
  - Uses Deformable Mirrors (DMs) to shape the wavefront
- Contrast can be maintained using Wavefront Sensing (WFS)
  - LOWFS uses PSF core light rejected by the reflective mask for WFS
  - OBWFS uses full out-of-band pupil illumination for high spatial frequency measurement
  - DMs and OTA segments used to preserve speckle-nulling WF
  - Performance depends on guide star magnitude – or a free-flying beacon...

Active Mirror PSFs



Simulated narrow-band PSFs at 200nm wavelength, for a UV telescope optimized for 300nm wavelength

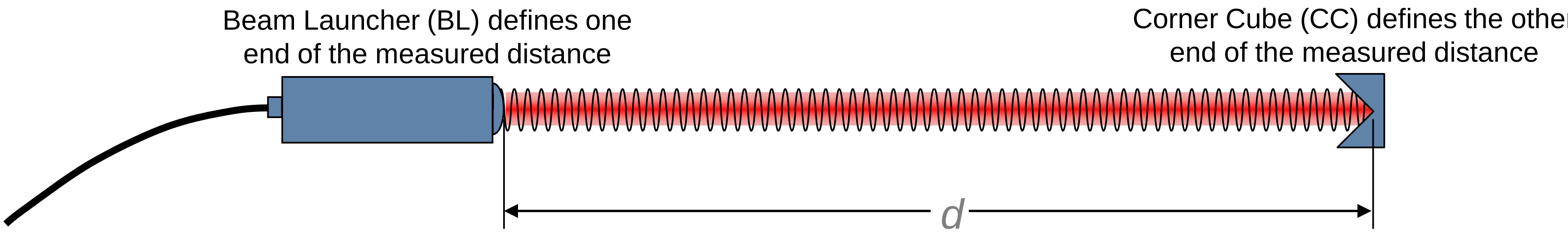
- Nominal WFE = 20nm
- Detector is critically sampled at λ = 300nm
- 400 actuators for control case

- AHMs and active SSMs, like Deformable Mirrors generally, have a different distribution of WFE vs. *ƒ* than conventional optics
  - Lower error in the low spatial frequencies
  - Higher error at and beyond the actuator spatial frequency
- This results in a tighter PSF core, but a raised "halo" in the sidebands
- Post-control PSF quality is a function of actuator density and initial WFE, and can be engineered to meet science requirements

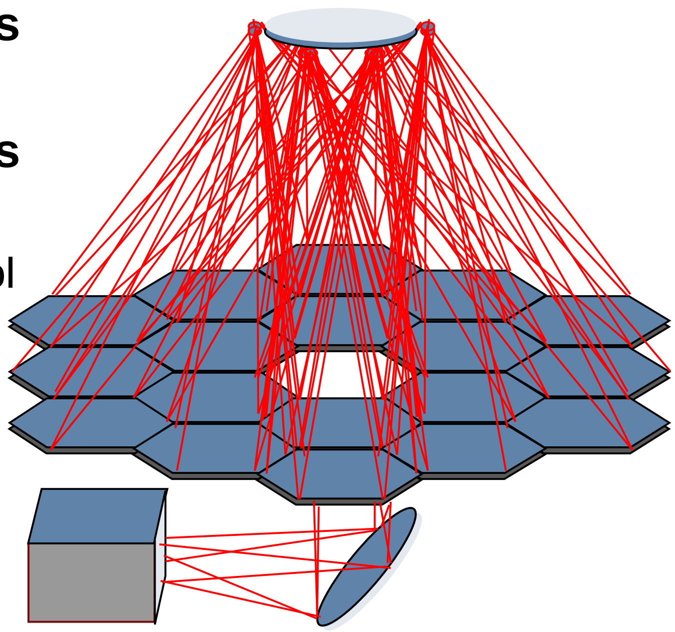
Coronagraphic Telescope Architecture Options

Ultra-Stability Architecture Options										
Instruments	**Aperture**	**Temperature**	**PM Mirrors**	**Mirror Thermal**	**Figure Actuation**	**Stabilization**	**Metrology**	**Sensing**	**Pointing Control**	**System-Level Testing**
Coronagraph	Monolithic	Heated to room temperature	Glass, closed-back	Stable material, slow control	Passive PM segments	Thermal control to <0.1 K	None	Image-based using science instruments	Spacecraft body-pointing using RWs	Component test at room & operating temp
Starshade Instrument	Segmented, not deployed	Controlled at lower temperature	Glass, open-back	Conductive material, fast control	Low authority PM FCAs	Thermal control to <0.001 K	Nanometer Metrology	Dedicated WFS	Fine Steering Mirror + SC	Partial system test at room temp
GA Imagers	Segmented, deployed	Uncontrolled, cryogenic	SiC		High authority PM FCAs	Metrology	Picometer Metrology	Starshade Tracker	Spacecraft body-pointing using thrusters	Partial system test at operating temp
GA Spectrometers	Segmented, assembled on-orbit				Coronagraph Deformable Mirrors (DMs)	WFSC during coronagraphy		LOS Guider		Full system V&V by analysis

A Laser Distance Gauge

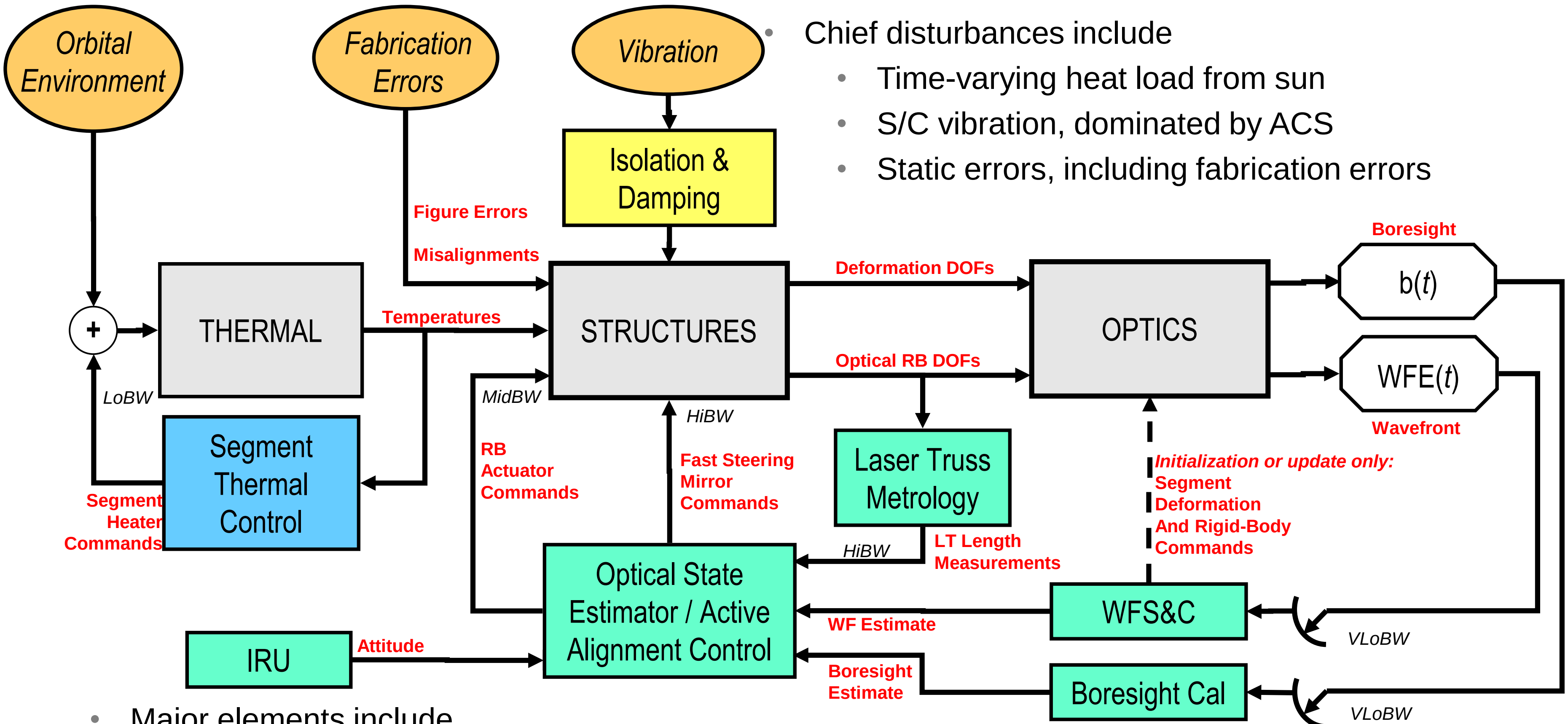


- A Laser Distance Gauge (LDG) is a "yardstick," with "inchmarks" provided by the interference fringes of the laser beam
- Six LDGs between each segment and the SM, and from the SM to the back end, allows measurement of all OTA alignment errors, at high BW
- **Slow position feedback to Segment RB actuators keeps the telescope aligned at low BW**
- **Fast feed-forward to a Fast Steering Mirror keeps the LOS constant and image jitter low**
  - Possible segmented DM could allow for fast FF control of segment DOFs as well
- **Or just SM control**



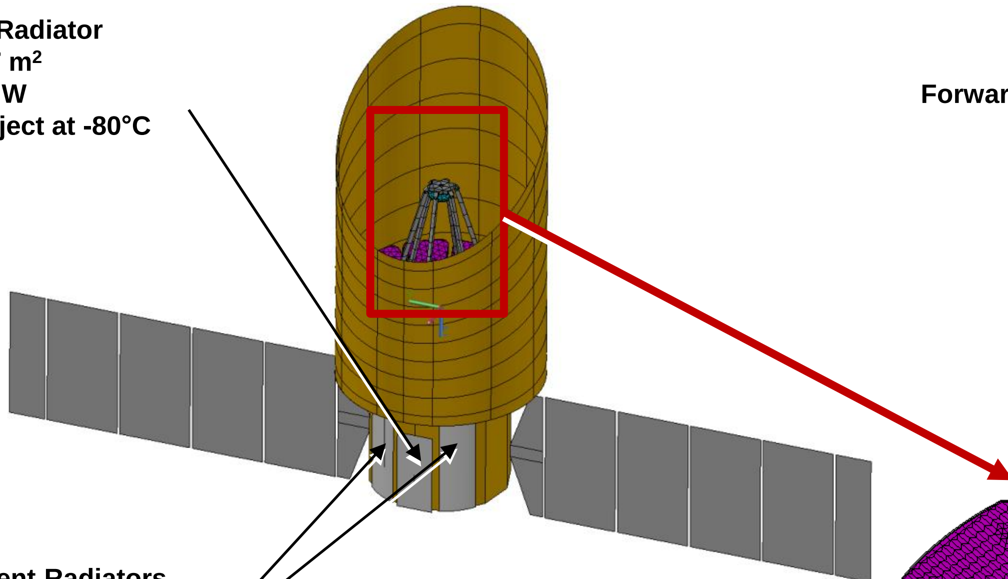
Control Block Diagram

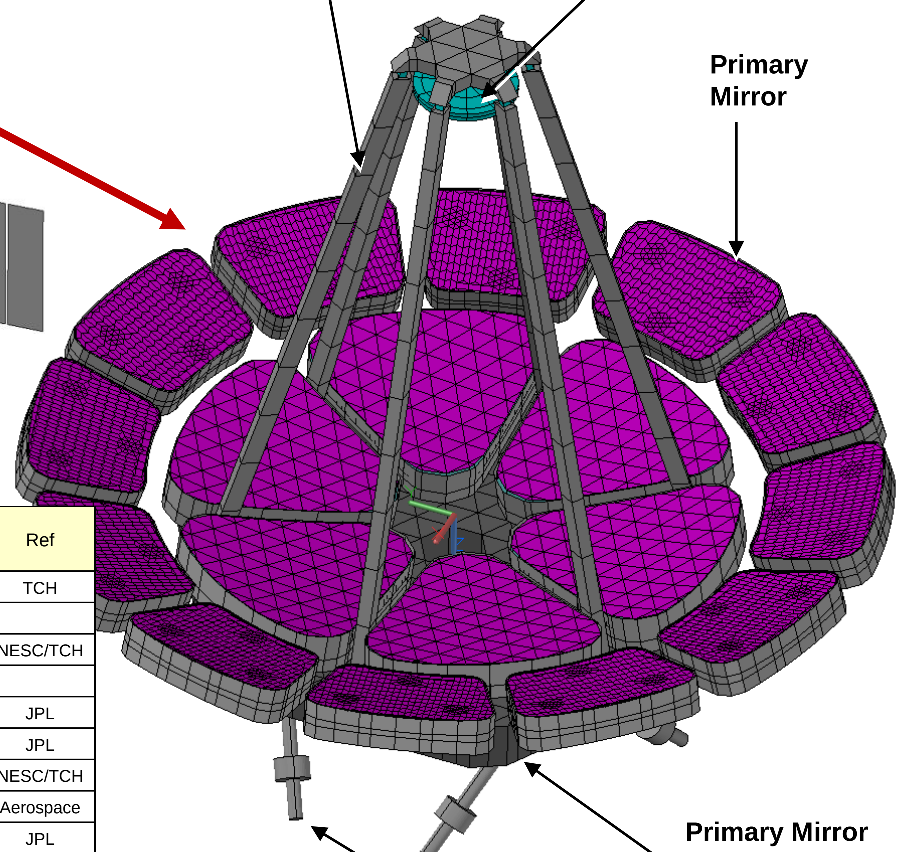
- Chief disturbances include
  - Time-varying heat load from sun
  - S/C vibration, dominated by ACS
  - Static errors, including fabrication errors



- Major elements include
  - Wavefront Sensing and Control
  - Laser Truss Active Alignment: active WF compensation and LOS pointing control
  - Segment Thermal Control to stabilize optical figure
  - Isolation and Damping to attenuate vibration disturbances

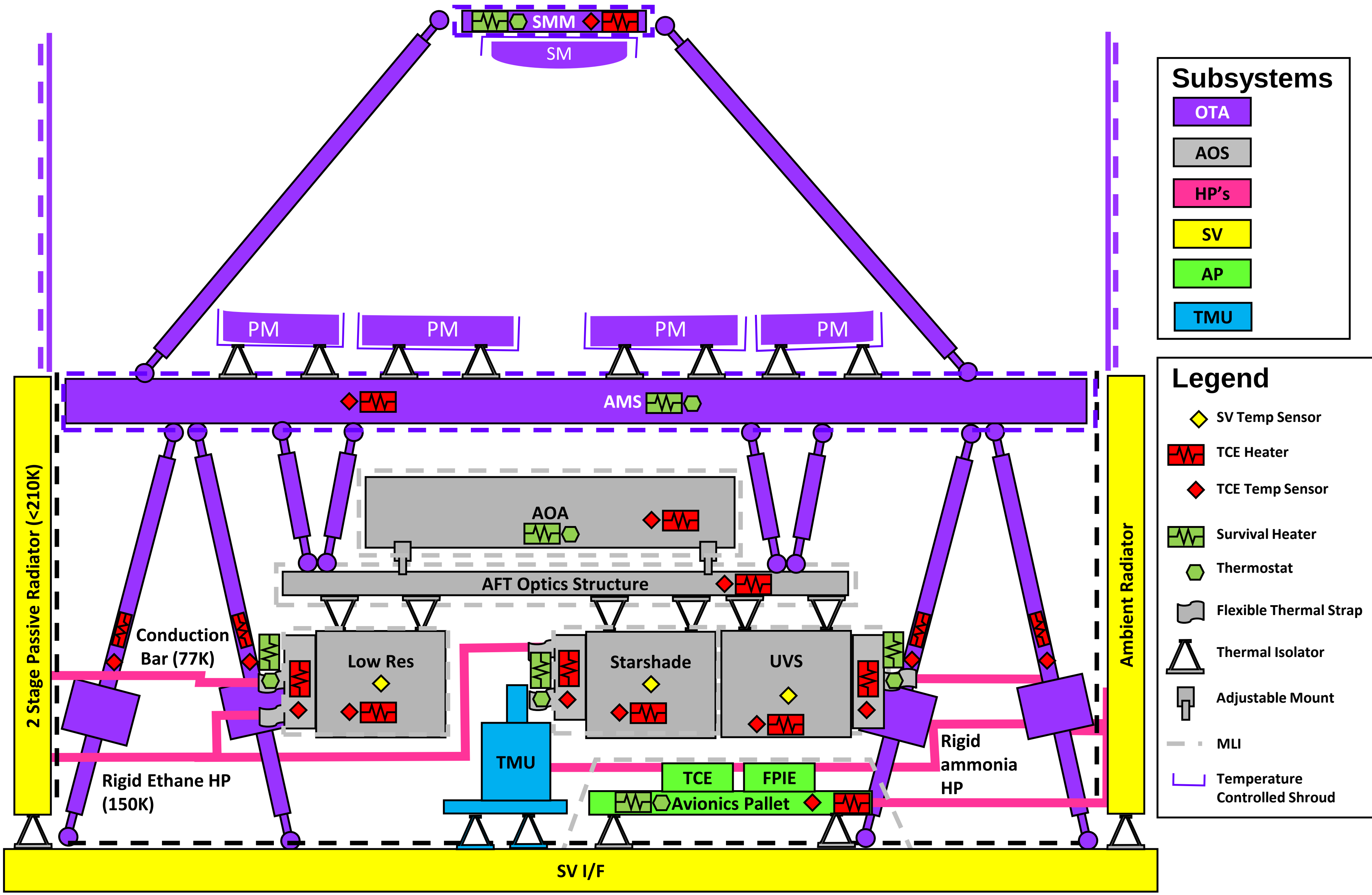
Thermal Model Overview





Material	Locations	BOL			EOL[a]			Ref
		α_S	ε_{IR}	α/ε	α_S	ε_{IR}	α/ε	
AL Mylar	PM Strongback closeouts	0.08	0.04	2.0	0.17	0.04	4.25	TCH
Bare ULE	Mirrors	0.7	0.7	1.0	0.7	0.7	1.0	
Black Kapton	Exterior MLI Blanks around optics	0.91	0.90	1.01	0.89	0.86	1.06	NESC/TCH
Silver Coating	Mirrors	0.04	0.02	2.0	0.084	0.025	3.36	
Solar Cells	Front Side of Solar Array	0.85	0.88	0.97	0.82	0.88	0.93	JPL
STAMET	Exterior MLI Blankets	0.5	0.85	0.59	0.6	0.8	0.75	JPL
Black Paint (Z306)	FMS, Baffles	0.97	0.91	1.07	0.92	0.87	1.07	NESC/TCH
White Paint (Z93)	VHF Diving Board and VHF Dipole	0.17	0.93	0.18	0.54	0.89	0.61	Aerospace
Effective Emittance [b]	Small MLI Blankets, Telescope		0.05			0.02		JPL
Effective Emittance [b]	Large MLI Blankets, OBA & Bus		0.04			0.01		JPL

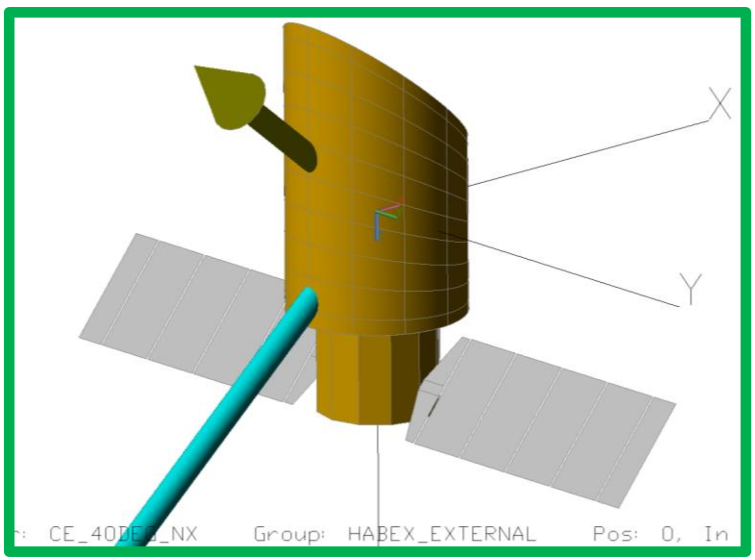
Thermal Block Diagram-LC6M



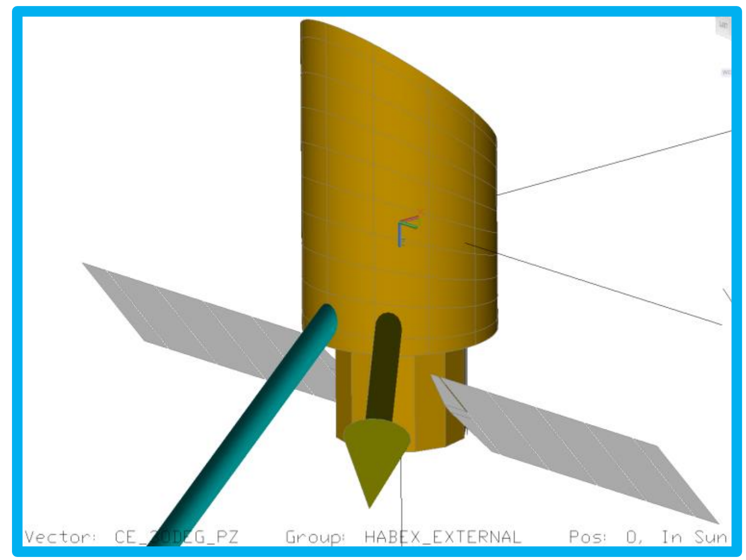
Analysis Cases

	Case Name	SS/ TR	SV I/F Temp (°C)	Material Properties	Solar Array Angle
SS1	SS1_HE_SVN40YDIR	SS	20	EOL	-40°
SS2	SS2_HE_SV30ZDIR		20	EOL	40°
SS3	SS3_CE_SVN40YDIR		-20	BOL	-40°
SS4	SS4_CE_SV30ZDIR		-20	BOL	40°
SS11	SS11_CS_SVN40YDIR		-40	BOL	-40°

Cases SS1, SS3 & SS11



Cases SS2 & SS4



Analysis Results

Subsystem/Component	Unit	Hot				Cold				Cold Surv	
		SS1		SS2		SS3		SS4		SS11	
		Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
TELE PM Inner Segments	(°C)	0.7	0.7	0.7	0.7	0.6	0.6	0.7	0.7	-37.9	-37.9
TELE PM Inner Segments (Abs)		-2.7	2.4	-2.7	2.4	-2.7	2.4	-2.8	2.4	-40.6	-36.7
TELE PM Outer Segments		-1.2	-1.2	-1.2	-1.2	-1.4	-1.4	-1.3	-1.3	-38	-38
TELE PM Outer Segments (Abs)		-9	5	-9	5	-9.2	5	-9.1	5	-43.8	-33.5
TELE SM		1.8	1.8	1.8	1.8	1.7	1.7	1.7	1.7	-37.8	-37.8
TELE SM (Abs)		0.4	2.9	0.4	2.9	0.3	2.9	0.3	2.9	-38.6	-37.2
TELE FMS		-85	-85	-84.6	-84.6	-87.1	-87.1	-86.8	-86.8	-99.8	-99.8
TELE FMS (Abs)		-113.2	0.3	-113.2	0.4	-115.1	0.1	-115.2	0.2	-121.7	-37.7
Aft Metering Structure		3.9	3.9	4	4	3.9	3.9	3.9	3.9	-35.5	-35.5
Aft Metering Structure (Abs)		3.9	3.9	4	4	3.9	3.9	3.9	3.9	-35.5	-35.5
OBA		-115.8	-24.6	-128.4	40.1	-117.6	-29.1	-130.2	34.4	-123	-35

Component	Power
AMS	191.4
Primary - Inner Segment	233.4
Primary - Outer Segment	372.9
Secondary	12.6
TOTAL	**810.3**

KEY TAKEAWAYS:

1. Minimal drift between cases
2. Minimal radius of curvature change due to bulk temp change
3. ~35W (inner segment) and ~31W (outer segment) needed for PM

Non-Deployed LC6Mnd Preliminary Mass Estimate

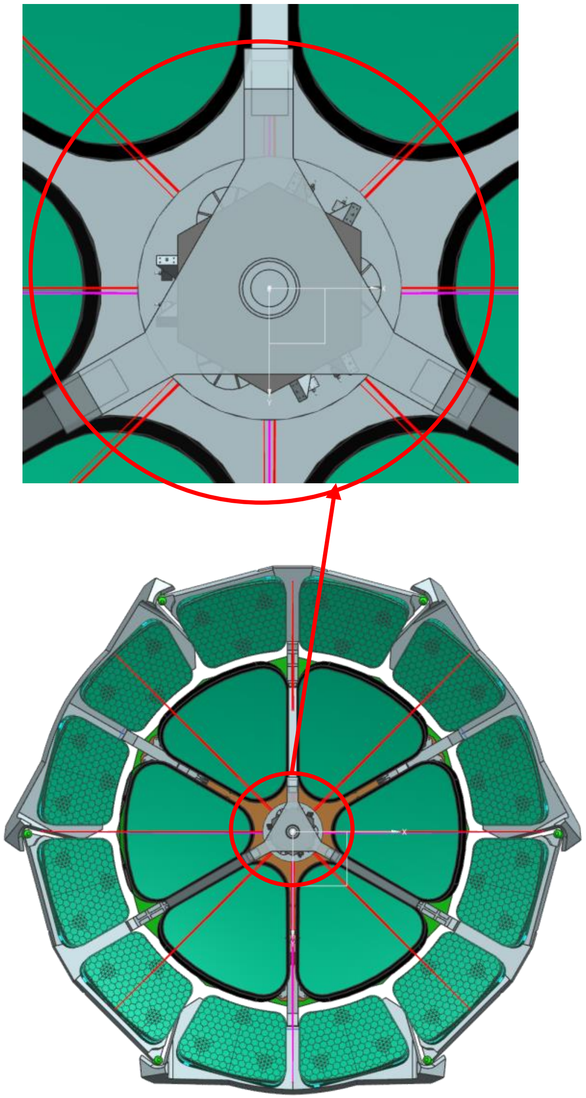
Element Name	ASM PARENT	Qty	Material	CBE Mass /Unit (Kg)	CBE MASS (kg)	JPL Uncertainty Factor	CBE Mass+JPL Uncertainty Factor
HABEX SEGMENT TELESCOPE Assembly (6m--18 Segment)	HABEX ASSY	1			**3917.0**	1.31	**5145.8**
Primary Mirror ASM	HABEX ASSY	1			1055	1.3	1371.2
Secondary Mirror ASM	HABEX ASSY	1			53	1.3	69.2
High LoRes IR ASM	HABEX ASSY	1			276	1.3	359.3
LoRes IR ASM	HABEX ASSY	1			200	1.3	260.1
Starshade ASM	HABEX ASSY	1			237	1.3	308.6
Electronics Assy	HABEX ASSY	1			160	1.3	208.0
Aft Metering Structure (AMS) Assy	HABEX ASSY	1			456	1.3	592.8
Secondary Support ASM	HABEX ASSY	1			195	1.3	253.5
Barrel Assembly	HABEX ASSY	1			586	1.3	761.7
Radiator Assembly	HABEX ASSY	1			215	1.3	279.5
Telescope to SC Strut ASM	HABEX ASSY	1			142	1.3	184.3
Cabling Assembly	HABEX ASSY	12			268	1.5	402.3
Dust Cover Assembly	HABEX ASSY	1			73	1.3	95.3
Spacecraft Bus Assembly					**2050**	**1.30**	**2665**
Launch Vehicle Assembly					**725**	**1.30**	**943**
Launch Dry Mass (inc. LV Interface)					6417		8396
BOL Mass (post Transfer Orbit)					6242		8168

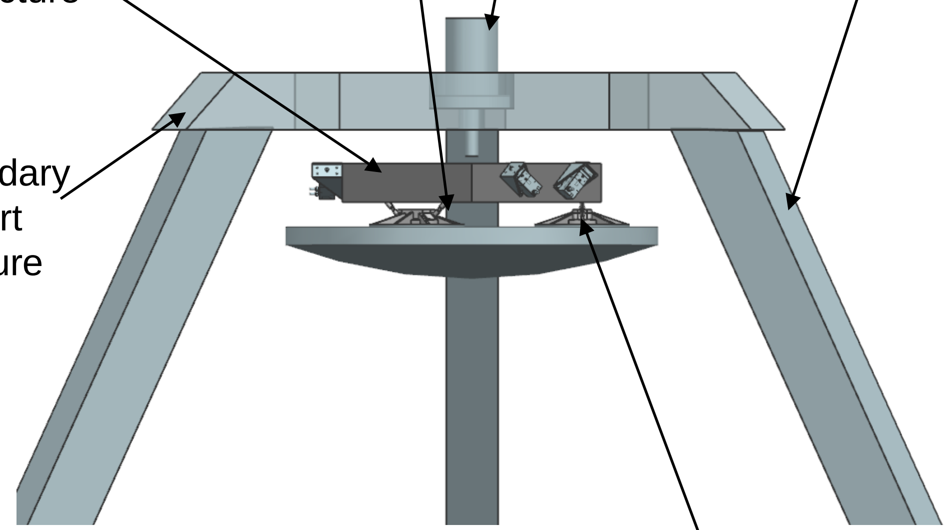
Update

Mass to C3

Atlas V 551	6,100 kg
Delta IV Heavy	9,800 kg
Falcon 9 Heavy	14,000 kg
New Glenn 3	17,000 kg

Secondary Mirror Assembly





Secondary Mirror

Temperature Results- Off Axis Segmented

Subsystem/Component	Unit	Hot				Cold				Cold Surv	
		SS1		SS2		SS3		SS4		SS11	
		Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
TELE PM Seg 1	(°C)	273.3	273.3	273.4	273.4	274.4	274.4	274.5	274.5	236.4	236.4
TELE PM Seg 1 (Abs)		269.7	274.9	269.9	275	271.9	275.8	272.1	275.9	235.2	237.1
TELE PM Seg 2		273.3	273.3	273.4	273.4	274.3	274.3	274.4	274.4	236.2	236.2
TELE PM Seg 2 (Abs)		269.6	274.9	269.8	275	271.9	275.7	271.9	275.8	235.1	237
TELE PM Seg 3		273.3	273.3	273.4	273.4	274.3	274.3	274.4	274.4	236.1	236.1
TELE PM Seg 3 (Abs)		269.7	274.9	269.9	275	271.8	275.7	272	275.8	235	236.9
TELE PM Seg 4		273.3	273.3	273.4	273.4	274.3	274.3	274.4	274.4	236.1	236.1
TELE PM Seg 4 (Abs)		269.8	274.9	269.9	275	271.7	275.7	271.9	275.8	235	236.9
TELE PM Seg 5		273.3	273.3	273.4	273.4	274.3	274.3	274.5	274.5	236.2	236.2
TELE PM Seg 5 (Abs)		269.7	274.9	269.9	275	271.9	275.8	272.1	275.9	235.1	237
TELE PM Seg 6		273.4	273.4	273.4	273.4	274.4	274.4	274.5	274.5	236.4	236.4
TELE PM Seg 6 (Abs)		269.7	274.9	269.9	275	271.9	275.8	272.2	275.9	235.2	237.1
TELE PM Seg 7		272.9	272.9	273.1	273.1	274.3	274.3	274.5	274.5	236.3	236.3
TELE PM Seg 7 (Abs)		270.4	275.1	270.5	275.2	272.3	276	272.5	276.1	235.3	237.1
PM Strong Back		276.9	278	276.9	278	276.7	278	276.8	278	237.6	238.1
AMS		275.9	275.9	275.9	275.9	275.4	275.4	275.7	275.7	236.9	236.9
AMS (Abs)		274.1	277.5	274.2	277.5	273.4	277.4	273.7	277.5	235.6	237.9
OBA		163.8	163.8	186.9	186.9	196.2	196.2	212.8	212.8	190.7	190.7
OBA (Abs)		117.6	200.4	127.6	269.3	134.8	238.8	153.1	259.4	132.4	229.4
Door		42.3	42.3	106	106	59.4	59.4	136.2	136.2	59.2	59.2
Solar Array		122	353.4	121.4	335	129.1	347.9	131.9	331.9	127.1	348.6

Heater Power-SS3 Cold Op Segmented

Zone	Description	PWR (W)		Zone	Description	PWR (W)
1	AMS_1A	14.41		15	PM_STRG_BCK_2A	12.64
2	AMS_1B	5.1		16	PM_STRG_BCK_2B	8.85
3	AMS_2A	14.85		17	PM_STRG_BCK_3A	12.98
4	AMS_2B	6.02		18	PM_STRG_BCK_3B	9.09
5	AMS_3A	15.34		19	PM_STRG_BCK_4A	12.99
6	AMS_3B	6.73		20	PM_STRG_BCK_4B	9.09
7	AMS_4A	15.33		21	PM_STRG_BCK_5A	12.64
8	AMS_4B	6.69		22	PM_STRG_BCK_5B	8.85
9	AMS_5A	14.86		23	PM_STRG_BCK_6A	12.25
10	AMS_5B	6.05		24	PM_STRG_BCK_6B	8.62
11	AMS_6A	14.41		25	PM_STRG_BCK_7A	3.49
12	AMS_6B	5.09		26	PM_STRG_BCK_7B	3.52
13	PM_STRG_BCK_1A	12.27				
14	PM_STRG_BCK_1B	8.62			**TOTAL**	**260.8**

Comments

- The current drift in the primary mirror segments looks promising for the required drift of the system. There is a simple bang on/bang off algorithm used with a 0.1K dead band that equates to 1 mK segment temperature drift or 7 pm RMS SFE drift over a 10 minute period.
- In addition to using a tighter dead band or PID algorithm, other methods such as moving the heater locations and adding mass, will help reduce the temperature drift.
- The monolith is more sensitive to temperature drift due to its larger diameter, however, the additional mass (thermal capacitance) will decrease the temperature drift.

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