End-to-end assessment of a large aperture segmented Ultraviolet Optical Infrared (UVOIR) Telescope architecture

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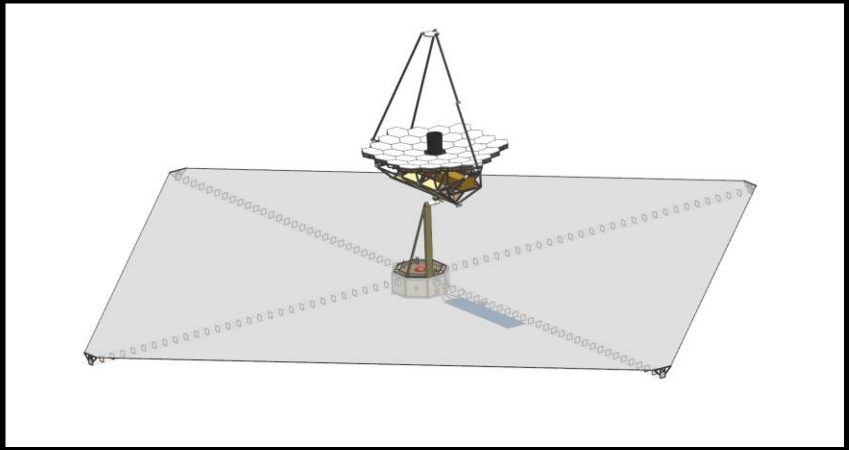


Key Science Drivers to Find Earth 2.0:

Need large diameter, many visits, 10^-10 contrast

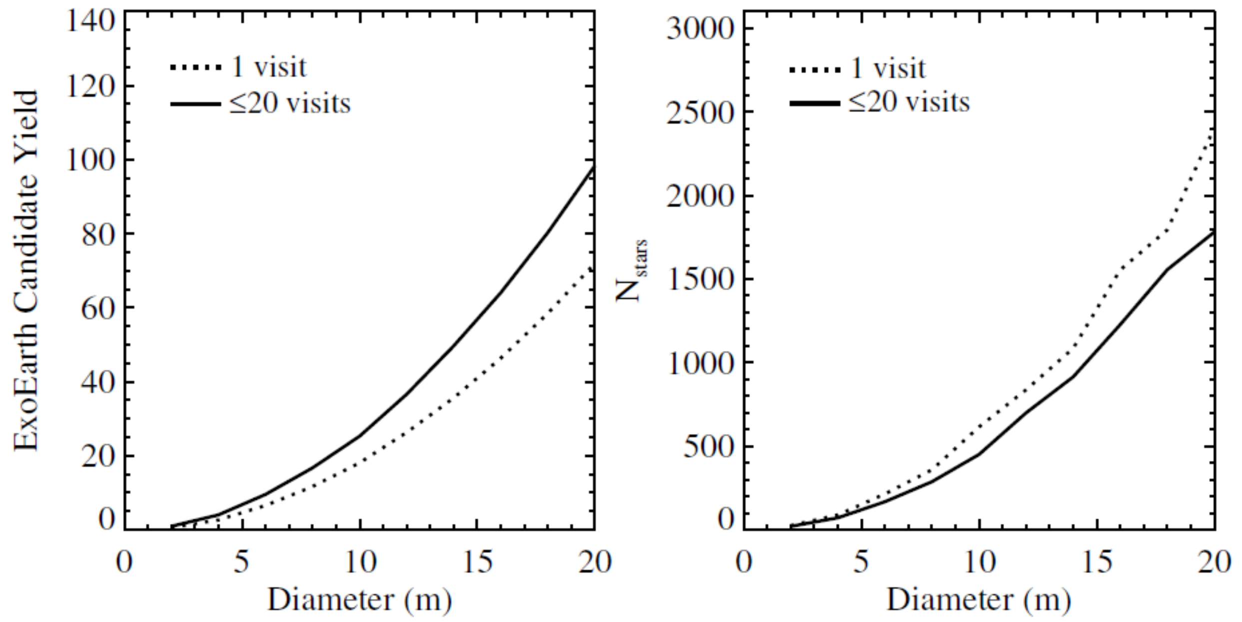
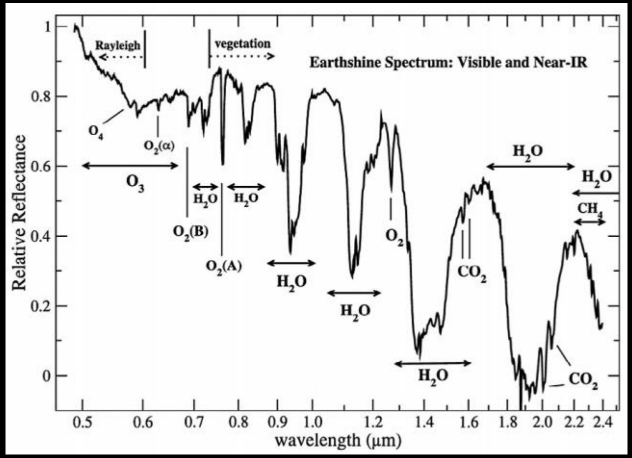


Fig. 5.— Comparison of ExoEarth candidate yield (left) and number of unique stars observed (right) as functions of aperture size for the single visit and multi-visit cases. No spectral characterization time is included in these calculations.

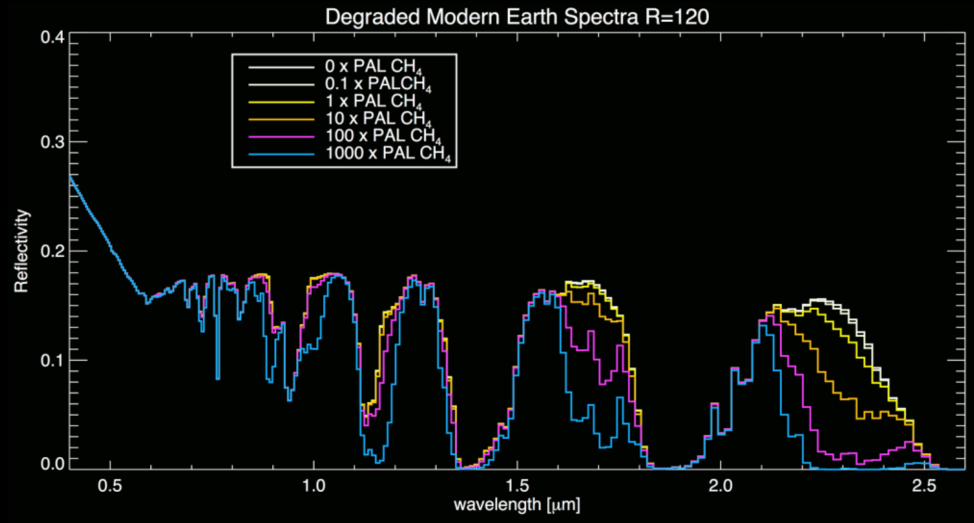
Lower Limits on Aperture Size for an ExoEarth-Detecting Coronagraphic Mission

Christopher C. Stark[1], Aki Roberge[2], Avi Mandell[2], Mark Clampin[2], Shawn D. Domagal-Goldman[2], Michael W. McElwain[2], Karl R. Stapelfeldt[2]

Need to Survey Lots of Spectrum



Earth Observed Reflectance Spectrum From HDST Report



Using Methane to Rule out False Positives (most H atoms are gone) – from S. Domagal-Goldman

General Approach taken since 2009

- To the extent it makes sense, leverage JWST knowledge, designs, architectures, GSE
  - Good starting point
  - Develop a full end to end architecture that closes
  - Try to avoid recreating the wheel except where needed
  - Optimize from there (mainly for stability and coronography)
- Develop a scalable design reference mission (9.2 meter)
  - Do just enough work to understand launch break points in aperture size
- Demonstrate 10 pm stability is achievable on a design reference mission
  - A really key design driver is the most robust stability possible!!!
- Make design compatible with starshades
- While segmented coronagraphs with high throughput and large bandpasses are important, make the system serviceable so you can evolve the instruments
- Keep it room temperature to minimize the costs associated with cryo
  - Focus resources on the contrast problem
- Start with the architecture and connect it to the technology needs

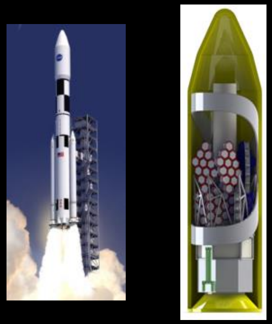
General ATLAST Requirements

Parameter		Requirement	Stretch Goal†	Traceability
Primary Mirror Aperture		≥ 8.0 meters	> 12.0 meters	Resolution, Sensitivity, Exoplanet Yield
Telescope Temperature		273 K – 293 K	-	Thermal Stability, Integration & Test, Contamination, IR Sensitivity
Wavelength Coverage	UV	100 nm – 300 nm	90 nm – 300 nm	-
	Visible	300 nm – 950 nm	-	-
	NIR	950 nm – 1.8 μm	950 nm – 2.5 μm	-
	MIR	Sensitivity to 8.0 μm††	-	Transit Spectroscopy
Image Quality	UV	< 0.20 arcsec at 150 nm	-	-
	Vis/NIR/MIR	Diffraction-limited at 500 nm	-	-
Stray Light		Zodi-limited between 400 nm – 1.8 μm	Zodi-limited between 200 nm – 2.5 μm	Exoplanet Imaging & Spectroscopy SNR
Wavefront Error Stability		~ 10 pm RMS uncorrected system WFE per wavefront control step	-	Starlight Suppression via Internal Coronagraph
Pointing	Spacecraft	≤ 1 milli-arcsec	-	-
	Coronagraph	< 0.4 milli-arcsec	-	-

Science Instrument	Parameter	Requirement
UV Multi-Object Spectrograph	Wavelength Range	100 nm – 300 nm
	Field-of-View	1 – 2 arcmin
	Spectral Resolution	R = 20,000 – 300,000 (selectable)
Visible-NIR Imager	Wavelength Range	300 nm – 1.8 μm
	Field-of-View	4 – 8 arcmin
	Image Resolution	Nyquist sampled at 500 nm
Visible-NIR Spectrograph	Wavelength Range	300 nm – 1.8 μm
	Field-of-View	4 – 8 arcmin
	Spectral Resolution	R = 100 – 10,000 (selectable)
MIR Imager / Spectrograph	Wavelength Range	1.8 μm – 8 μm
	Field-of-View	3 – 4 arcmin
	Image Resolution	Nyquist sampled at 3 μm
	Spectral Resolution	R = 5 – 500 (selectable)
Starlight Suppression System	Wavelength Range	400 nm – 1.8 μm
	Raw Contrast	1×10^{-10}
	Contrast Stability	1×10^{-11} over science observation
	Inner-working angle	34 milli-arcsec @ 1 μm
	Outer-working angle	> 0.5 arcsec @ 1 μm
Multi-Band Exoplanet Imager	Field-of-View	~0.5 arcsec
	Resolution	Nyquist sampled at 500 nm
Exoplanet Spectrograph	Field-of-View	~0.5 arcsec
	Resolution	R = 70 – 500 (selectable)

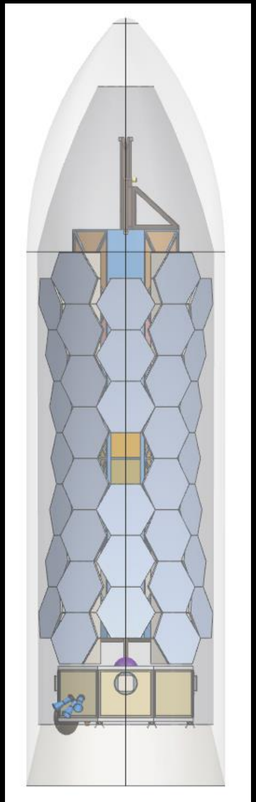
Adapted from Rioux, et al, 2016, JATIS, in review

Aperture Sizes Studies since 2009
Using JWST Hex Segment Architectures

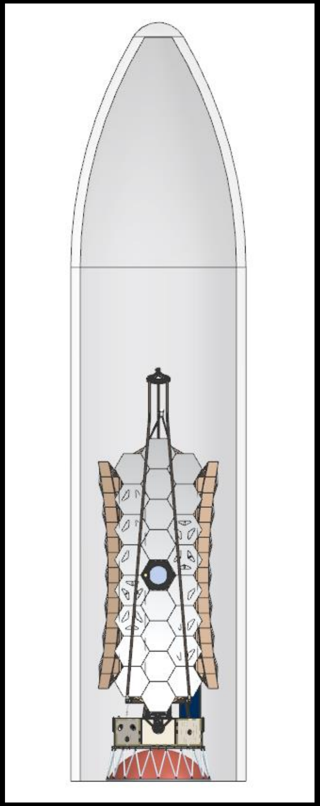


Space Launch System
Launch Vehicle/Panels in Notional Shroud

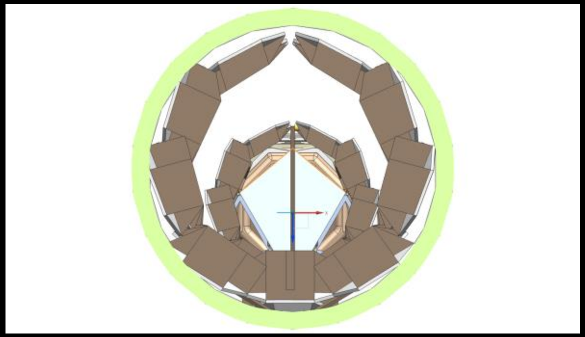
9.2m in Delta IVH:
Circular Geometry
JWST SM deployment,
3 JWST-wings per side



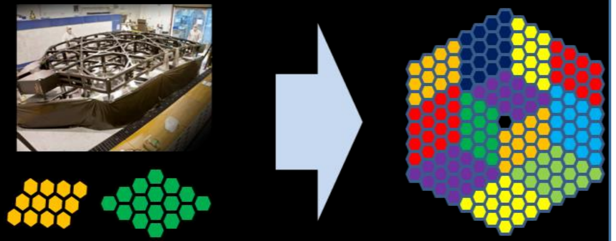
11.9m in Delta IVH
Clamshell SMSS

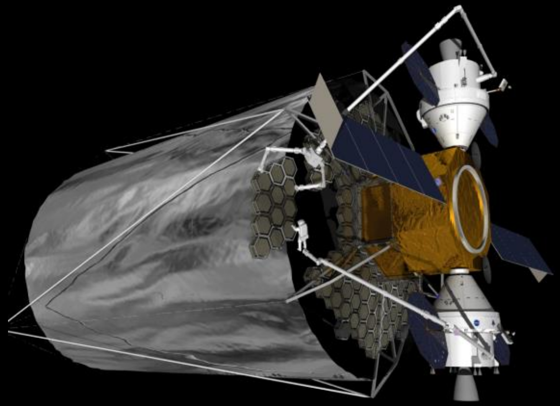


12m is SLS,
Dual Fold
Wing



18m in Block 2 SLS,
16m deemed
feasible

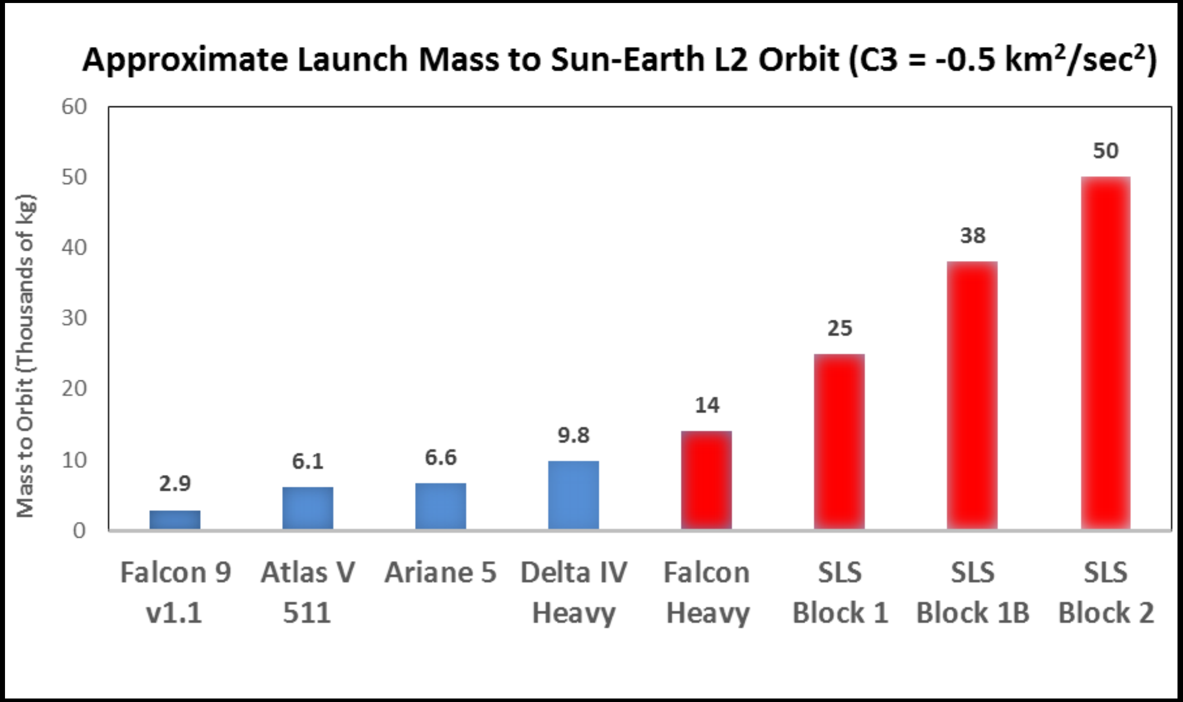


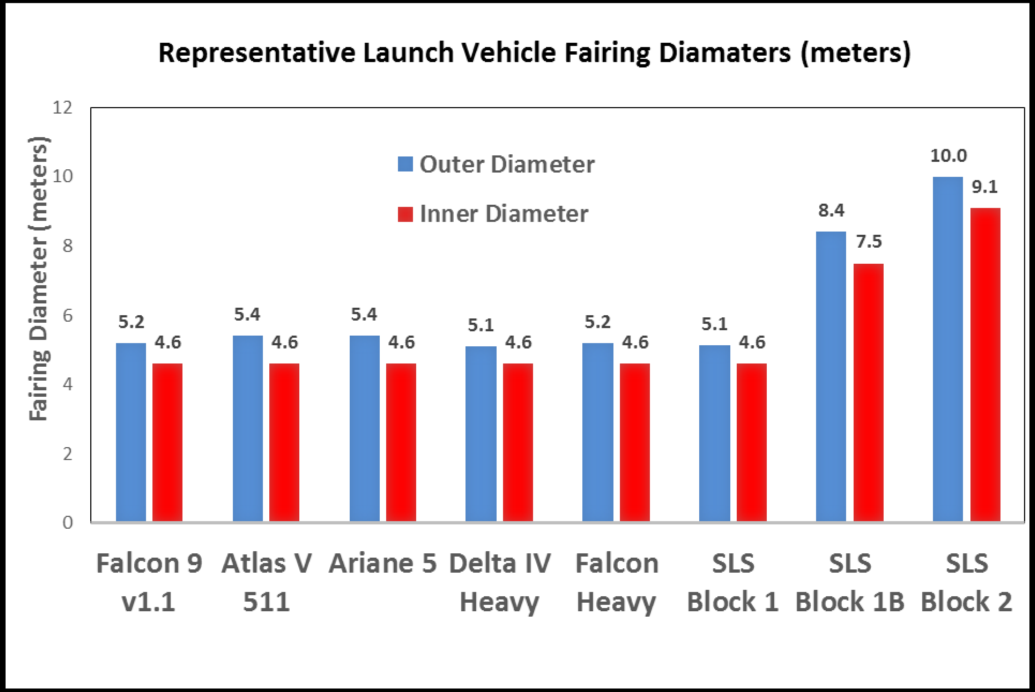


20m Assembled

SIZE

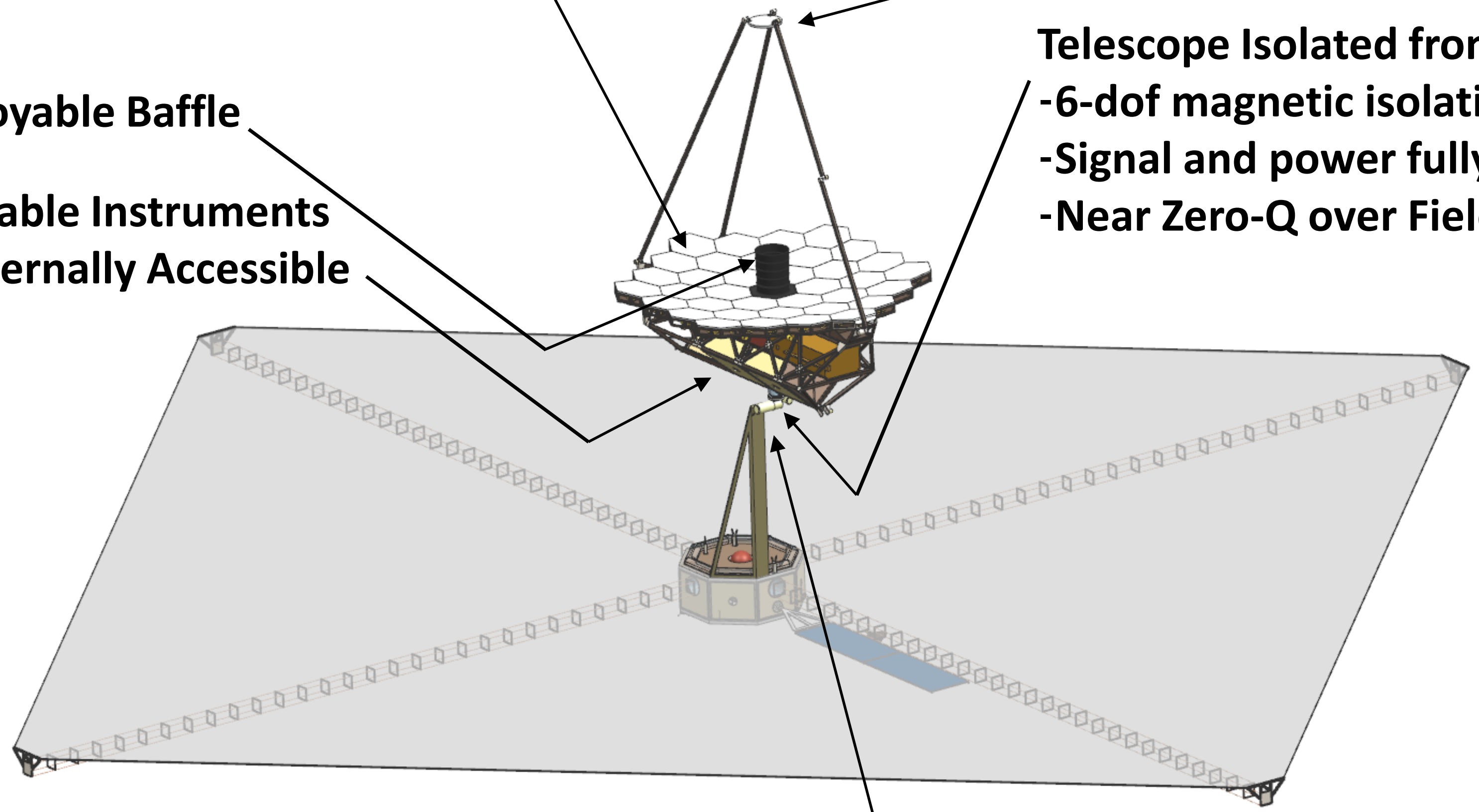
Mass Considerations



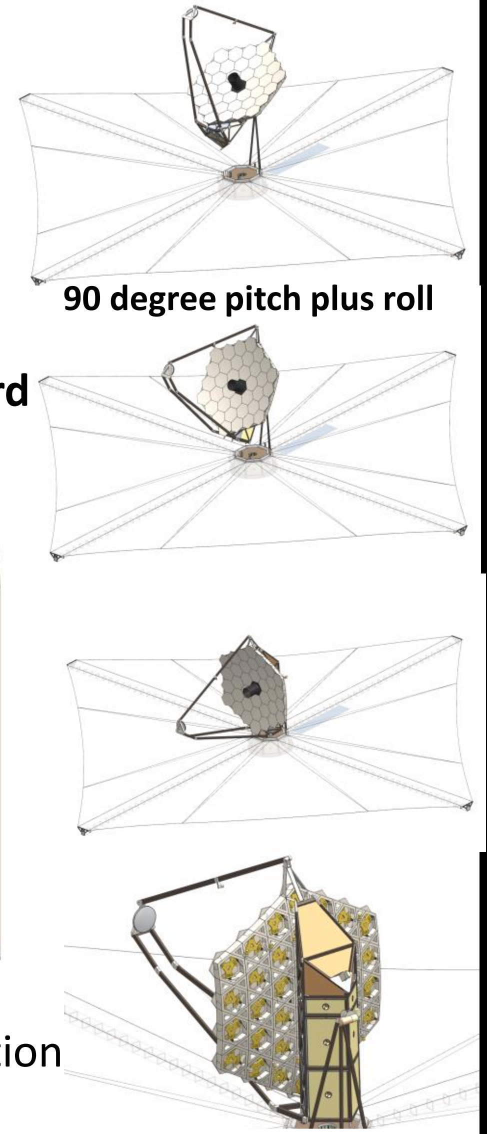


For a 12m, goal of 50% mass reserves and sufficient volume drives us towards SLS Block 1B or 2

Scalable Segmented Design Reference Mission



Stowed
Configuration

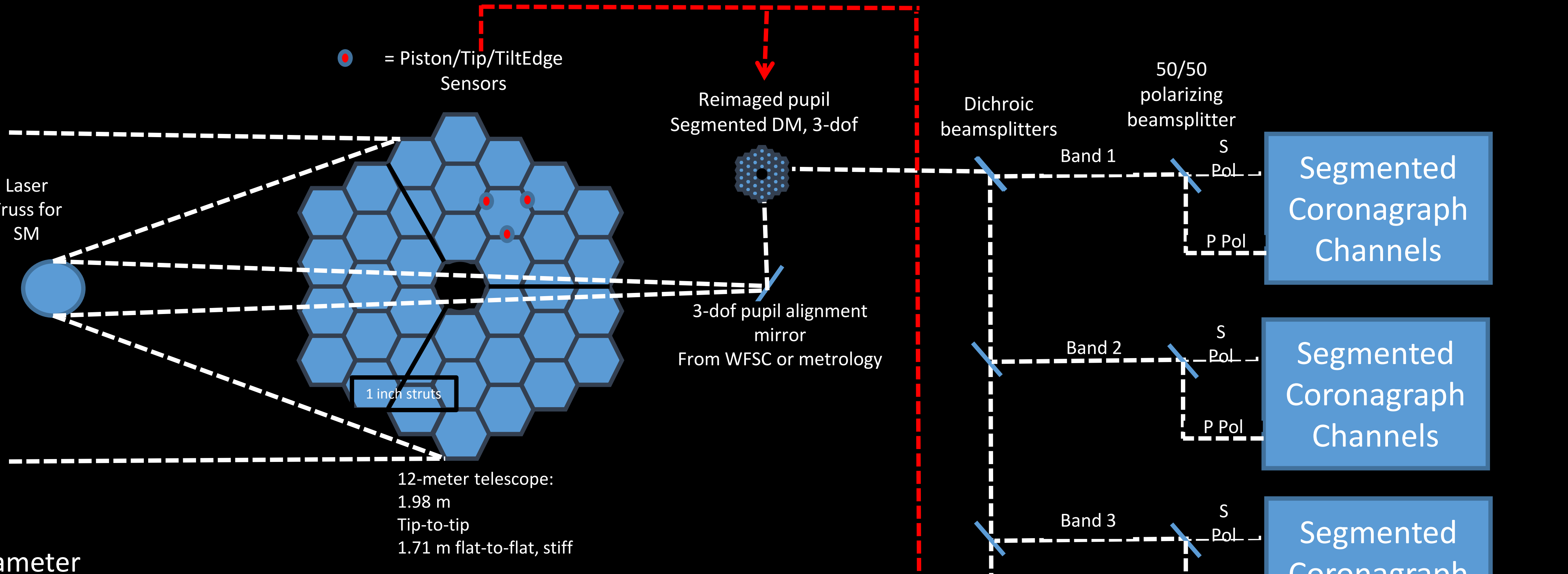


90 degree pitch plus roll

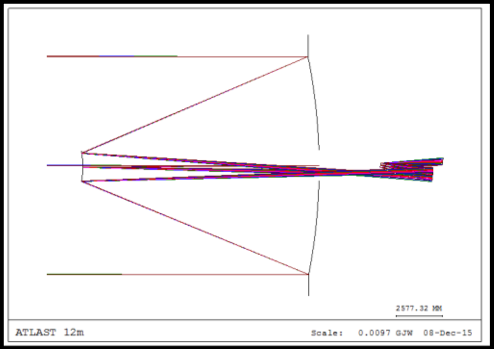
Multi-layer stability approach: Add layers based on performance and cost

	Layer 1: Minimum observatory (active heater, non-contact isolation)	Layer 2: Use internal coronagraph sensing and control methods	Layer 3: Use telescope metrology systems
Segment Thermal Stability	Low Q architecture, Active PM heater control, material choice	Zernike Sensor with continuous DM control	
Segment to Segment Thermal Stability	Active heater and MLI control, material choice, joint design	Zernike Sensor with Continuous or Segmented DM control (piston, tip/tilt), Use bright star (reduce 10 minute update rates)	Laser metrology, edge sensors
Segment Dynamics Stability	Stiffness and Design, Possibly smaller segments, materials		
Segment to Segment Dynamic Stability	Reaction Wheel isolators, Non-contact Isolation between SC and telescope, Design, TMD's (if needed), material choice	Zernike Sensor, Feed forward DM control, Use bright star (reduce update rate)	Laser metrology, edge sensors
Line of Sight/SM Thermal Stability	Low Q architecture, Heater	LOS sensor and control mirror, MIMF for SM alignment	Laser truss, image based techniques
Line of Sight/SM Dynamic Stability	Reaction wheel isolators, Non-contact isolation, Design, TMD (if needed)	LOS sensor and control with feed forward control	Laser truss, imaged based techniques

Notional End to End Architecture
(Backplane size invariant)



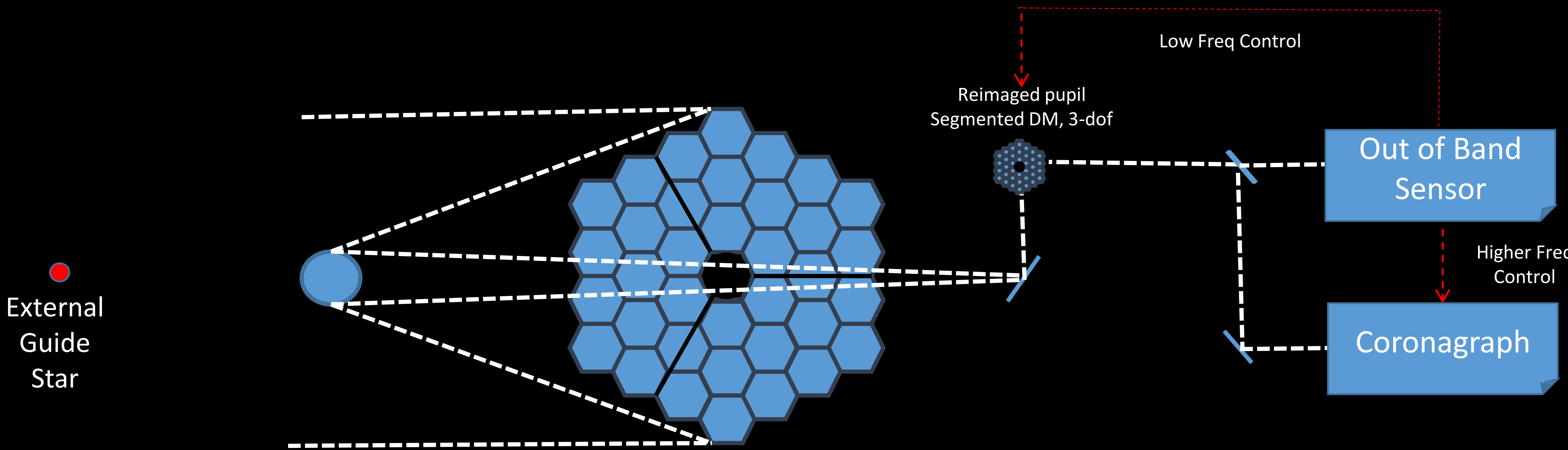
12m diameter
PM to SM spacing : 13m
SM obscuration is 19.5% area
Design for 8x12 arcminutes
TMA
Coronagraph uses PM-SM



Optical Beacon Allows for Faster Sense and Control

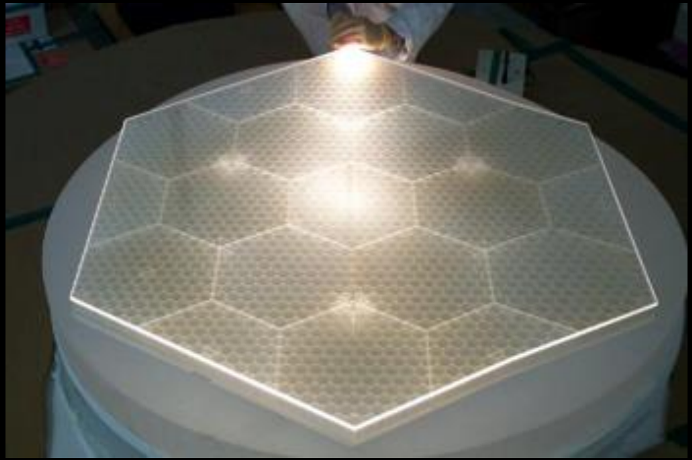
Allows Adequate S/N for Fast Sensing and Control

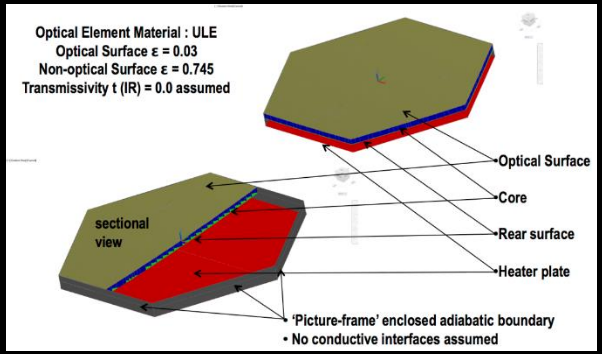
Can we relax requirements on telescope

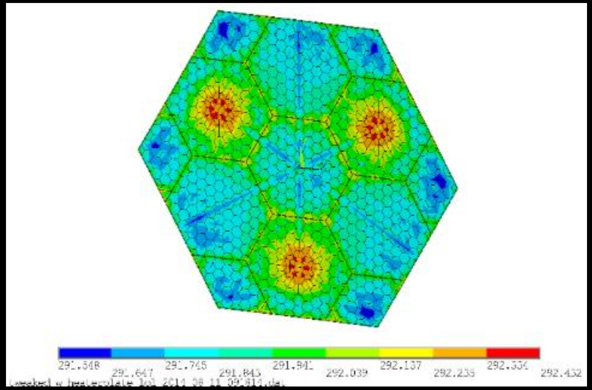


Mirror stability demonstrated

AMSD: Lightweight Closed Back ULE Heritage







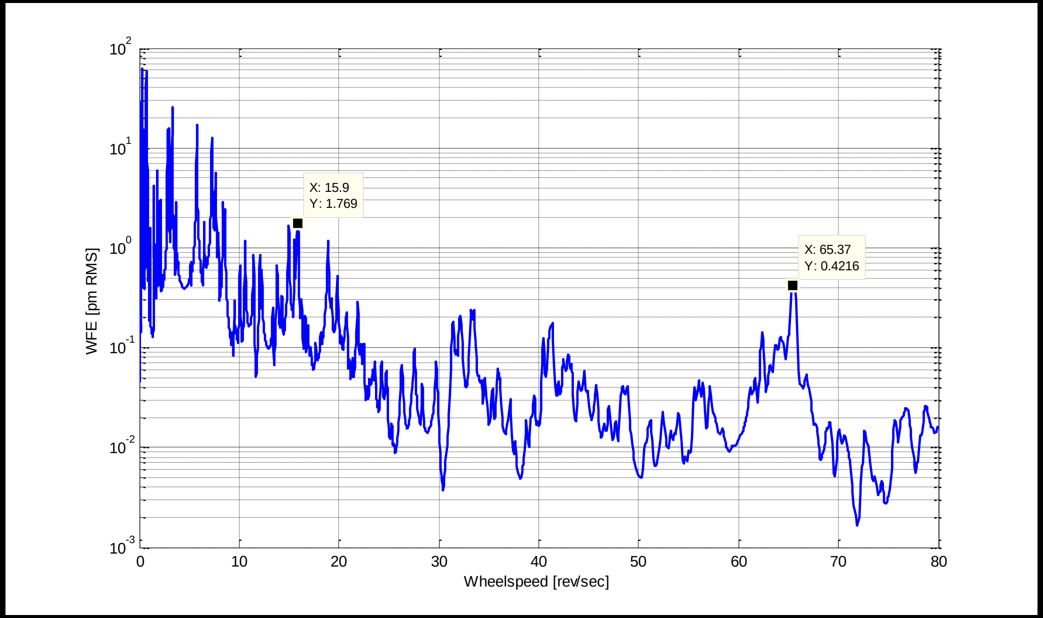
- See paper by M. Eisenhower/SAO on mirror thermal control architecture
  - Next generation ULE 1.2m flat to flat, 12Kg mass
- Single segment design is optimized for high thermal and dynamic stability (each segment is like a smallish ExoC or TPFC mirror)
- Mass production is similar to TMT, multiple parallel lines
- Silicon Carbide and Zerodur also assessed and each has advantages, expect mirror material trade in the future

	.98mK control		1.27mK control	
CTE Distribution	RMS (pm)	PV (pm)	RMS (pm)	PV (pm)
Mirror 1	3.8	13.9	4.94	18.1
Mirror 2	0.514	1.82	0.67	2.38

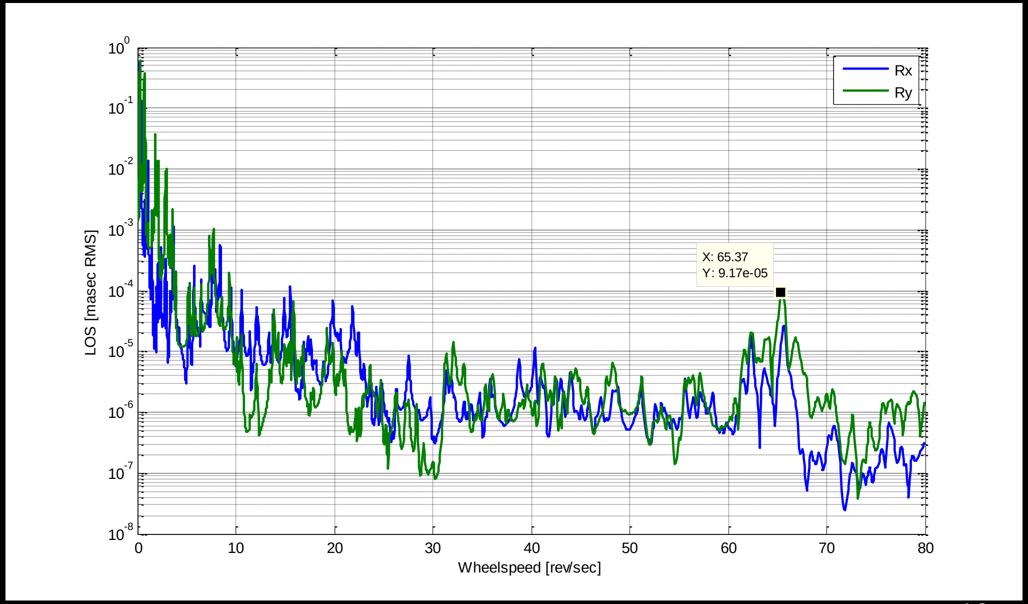
Integrated Modeling Results

- Based on published non-contact isolation values, passive reaction wheel isolation
- Caveats:
  - Results include NO MUF and damping knock-down factor.
  - Mechanical and finite element models are at preliminary stages of development.
  - All isolation systems are implemented as idealized analytical filters.
  - Assumes system behaves linearly down to picometer scale (plan to validate this at joint/interface level, Ultra-Stable technology effort underway)

Total WFE: Vibe+RW Isolators, 1" Strut



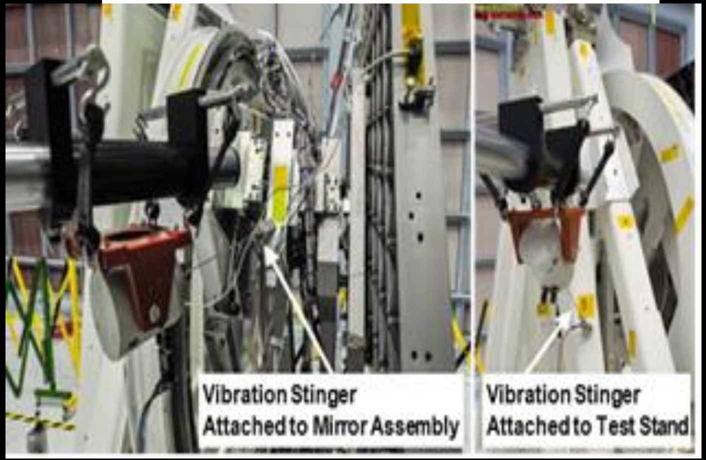
LOS Results: Vibe+RW Isolators

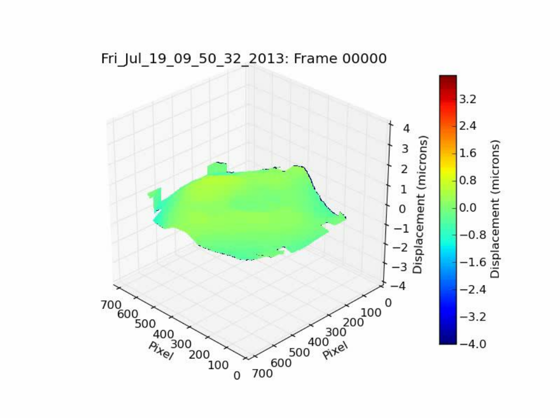


Mirror dynamics and deformations

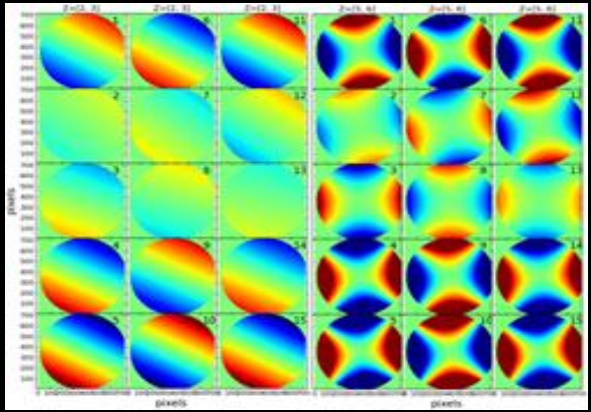
- Mirrors will have tilt modes that dominate WFE along with deformation modes that result from harmonic coupling
  - Deformations also result from tilts (induced by the inertia), see below
- One path to minimizing mirror tilt and mirror deformation is to minimize the tilts using isolation – initial modeling of tilts using traditional linear models is promising but hard to verify full scale at the picometer level
- A more robust solution and simpler verification strategy for mirror tilt is an active control loop with a segmented DM. In this approach, larger tilts can be tolerated but only if they do not deform the mirror. This also provides insurance from higher order harmonics and sneak paths like cables.
  - 2x stiffer mirrors would greatly reduce the risk of higher order of harmonics
  - Stiffer mirrors also help with gravity SAG
- See induced deformation (see“nanometer characterization of the JWST optomechanical systems using high-speed interferometry”, Saif et al, Applied Optics May 1st 2015 Vol 54, No. 13”)

Input disturbance locations used during dynamic high speed interferometer metrology

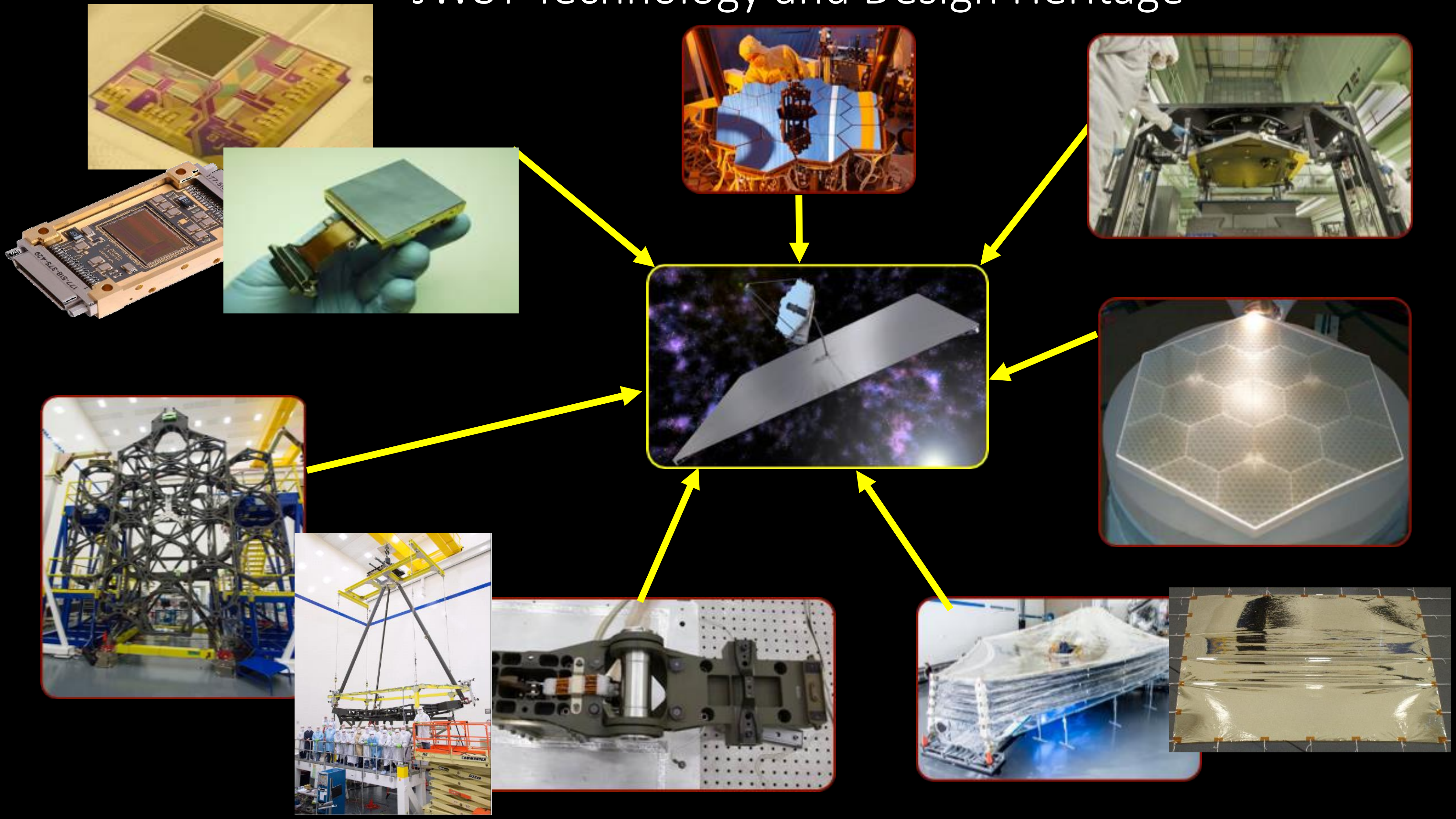




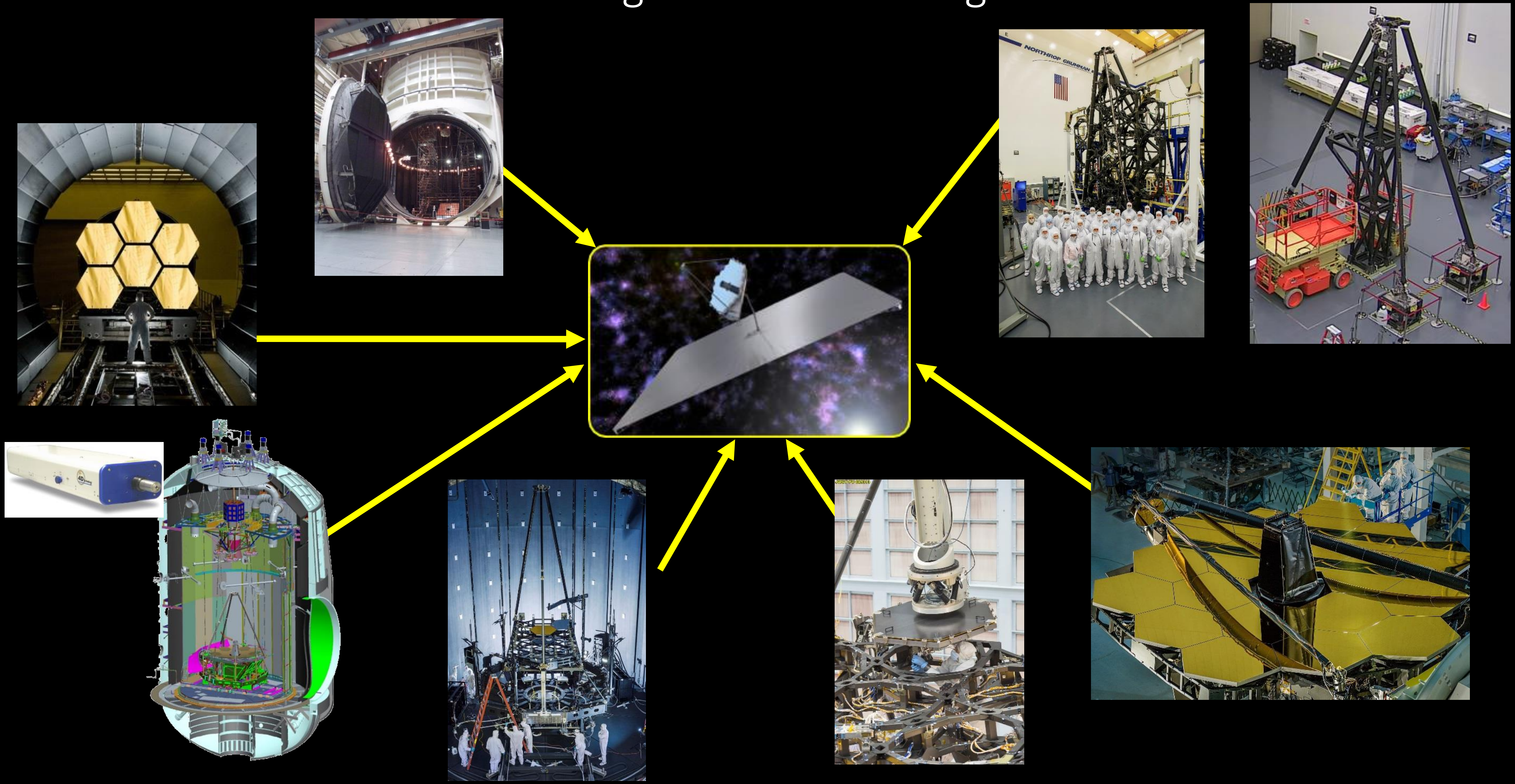
Spatial Modes of a mirror segment demonstrates rigid body and deformation modes



Large Aperture UVOIR Telescope Can leverage JWST Technology and Design Heritage



Large Aperture UVOIR Telescope Can Leverage JWST Integration and Testing



Challenges/Future Work

- Continue to work out ways to actively control out the stability (at least thermal stability)
  - Work out the details on whether a beacon/CoC sensor will work
  - Edge sensors
  - Error budget/sensitivities
- Polarization
  - Can we solve it without beamsplitting?
  - Can we manage the leakage terms (ghosts)
- Throughput
  - What can we do to minimize reflections or improve throughput
  - Lots of simultaneous bands can help?

Conclusion

- A end to end scalable segmented telescope architecture that achieves high stability continues to evolve
- JWST segment geometry and size has given us a good starting point for a reference design
  - Continue to evaluate improvements like strut size on a case by case basis
- Some key technologies that enable this:
  - High contrast segmented coronagraphs
  - Fast Sense and Control Technologies (edge sensors, optical beacons)
  - Picometer class Segmented DM’s, faster is better
  - Ultra-stable structures and latches, slow drifts may be OK, no lurching
  - Optical components for high contrast (dichroics, beamsplitters, polarization)
  - Picometer stable mirrors (milli-Kelvin class thermal control)
  - Low power laser truss for secondary mirror