Beyond JWST: Mirror Technology

Notes for Discussion 11/15/13

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Mirror Tech Group Scope and Task

- **Task**
  - What capabilities are needed? For ATLAST, to achieve science goals
  - Where are we now? Identify current capabilities…
    - JWST, SIM, AMD, NASA tech, other tech
  - Where will we be in 10 years? Extrapolate capabilities w/o additional investment
  - What do we need beyond expected development? Identify areas where additional funding is required to develop needed capabilities
    - Competed development – AMSD-like program model
- **Mirror Technology Scope**
  - Requirements flow down to the OTA level
  - Mirror technology
    - Glass, SiC, composite, metal…
  - Wavefront control at the OTA level
    - WFS&C
    - Actuators
    - Metrology
    - Vibration suppression

ATLAST Requirements

ATLAST Requirements from Science Drivers to date*

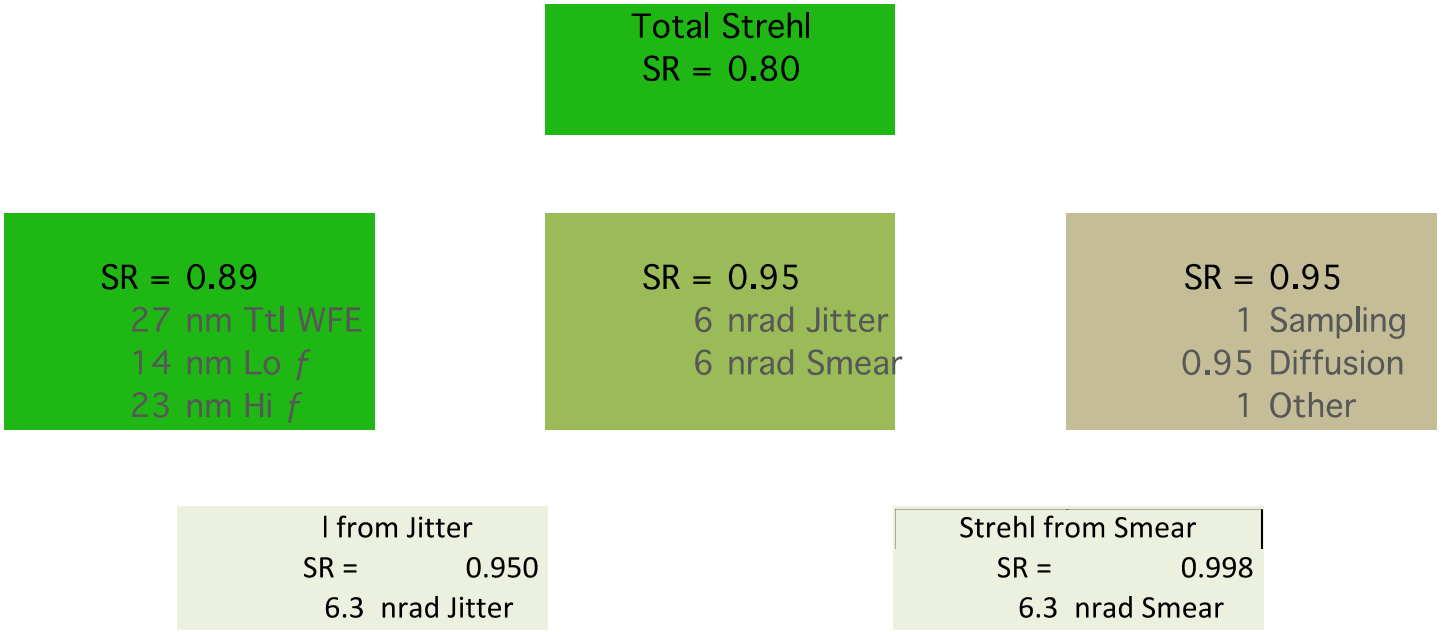
Telescope Parameter	Consensus Value
Primary mirror diameter	≥ 8 meters
UV Sensitivity	900 Å – 3000 Å
Vis / NIR Sensitivity	0.3 μm – 2.5 μm (5 μm)
Pointing stability	~1.3 – 1.6 mas
Optical performance:	
General Astrophysics	Diffraction limited at 0.5 μm
Exoplanet Observations	0.01 – 0.1 nm WFE with active control in coronagrph

Instrument Parameters	Consensus Value
Starlight suppression	10^{-11} down to IWA ~40 mas
UV Spectroscopy	R = 20,000 – 150,000
Exoplanet Spectroscopy	R = 70 - 500
Vis / NIR Imaging	FOV: 4 – 8 arcmin, Nyquist
UV Imaging	FOV: ~1-2 arcmin

- **This talk provides a *very preliminary* look at the flowdown of ATLAST requirements and constraints to ATLAST mirrors**
- **We also mention a key constraint: the Launch Vehicle**
- **Driving requirements are circled at left**

***From M. Postman, "Science Requirements for a 2030-era UVOIR Space Telescope," Aug. 7, 2013, presented here by M. Werner.**

Preliminary Flowdown to Strehl and WFE



- **Driving requirements:**
  - "Diffraction limited at 500 nm," interpreted as 80% Strehl
  - "Pointing stability < 1.6 mas," limits the LOS contribution to Strehl
- **Flowdown, assuming 8 m aperture:**
  - Total WFE ≤ 27 nm RMS
  - Jitter and smear ≤ 6.3 nrad

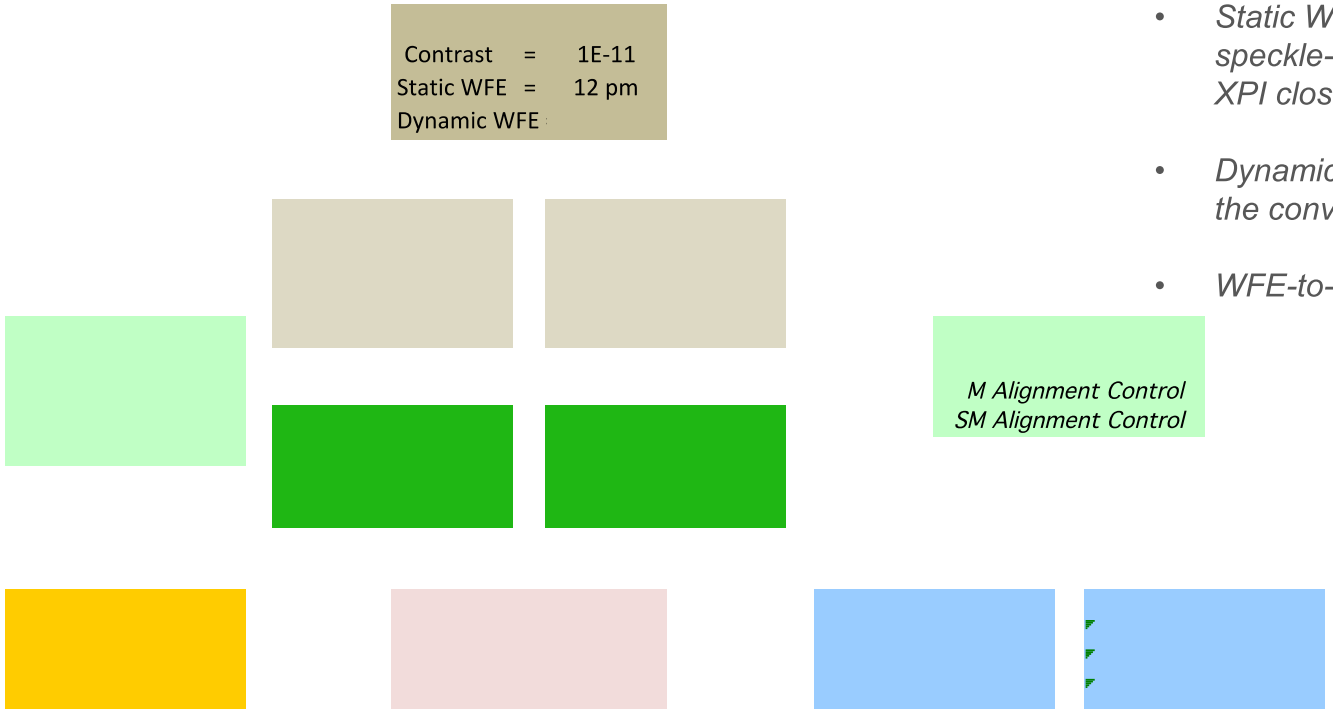
Preliminary Flowdown of WFE to Mirrors

- *WFE at Cassegrain focus, after Wavefront Control*

		27 nm Total 14 nm Lo *f* 23 nm Hi *f*	32 nm Spec 18 nm Margin 80 % EE		
SM Alignment Control					
	Static WFE 24 nm 10 nm Lo *f* 22 nm Hi *f*	4 4 0		10 nm 8 nm Lo *f* 6 nm Hi *f*	
22 nm 8 nm Lo *f* 21 nm Hi *f*	8 nm 7 nm Lo *f* 4 nm Hi *f*	5 nm 1 nm Lo *f* 5 nm Hi *f*	5 nm 5 nm Lo *f* 2 nm Hi *f*	rument Errors 1 nm 1 nm Lo *f* 0 nm Hi *f*	8 nm 6 nm Lo *f* 6 nm Hi *f*
9 nm 5 nm Lo *f* 8 nm Hi *f*	19 nm 3 nm Lo *f* 19 nm Hi *f*	7 nm 5 nm Lo *f* 5 nm Hi *f*	4 nm 4 nm Lo *f* 2 nm Hi *f*	3 nm 3 nm Lo *f* 1 nm Hi *f*	3 nm 3 nm Lo *f* 0 nm Hi *f*

- **WFE is allocated between dynamic (drift) and static WFE**
  - Will require further study to refine
- **Component level performance required will be quite challenging**
  - PM WFE = 19 nm (static) and 3 nm (dynamic)

Preliminary Look at Contrast

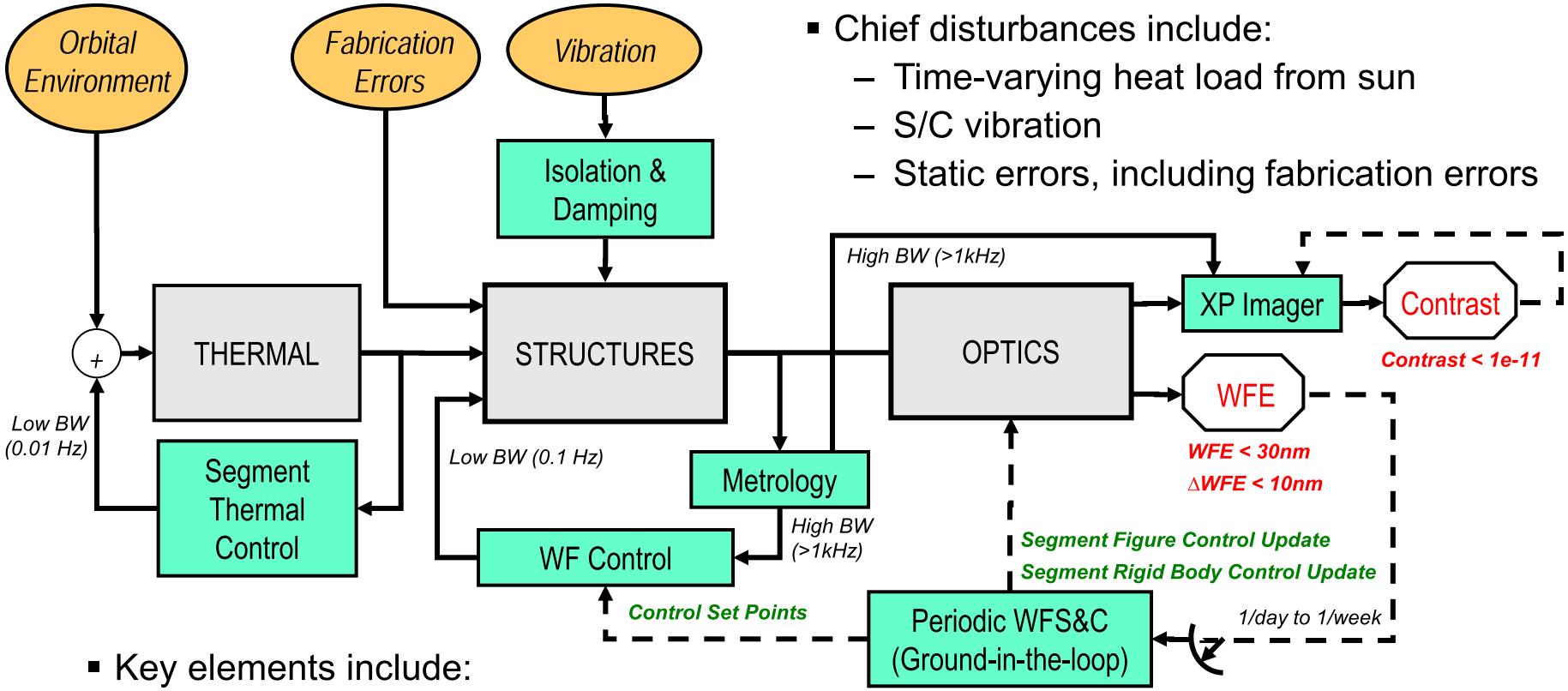


- *Static WFE is with respect to a speckle-nulling condition achieved in XPI closed loop DM control*
- *Dynamic WFE is the drift away from the converged static WF*
- *WFE-to-contrast from Shaklan et al*

- **Flow of contrast errors is through additional WF control stages in the ExoPlanet Instrument (XPI)**
  - Possibly aided by high bandwidth Metrology
- ***Very high control gains* are needed for XPI, to reduce the WFE drift to that required for high contrast**

Control Block Diagram

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



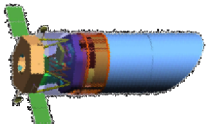
- Key elements include:
  - Thermal Control to stabilize optical figure
  - Isolation and Damping to attenuate vibration disturbances
  - Periodic Wavefront Sensing and Control to update control setpoints
  - Metrology to measure drift away from setpoints
  - Active (movable / deformable) Optics to implement control commands
  - Exoplanet Imager (XPI) with closed-loop contrast control and maintenence

Mirror Technology: Glass Mirrors

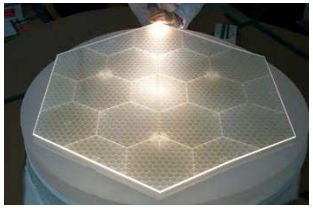
Very Large ULE Monoliths

HST Primary

- Size to 2.4m demonstrated
  - Growth to 4 - 8 m is possible using modern methods
- <10 nm rms SFE
- <5 Å microroughness
- 50 kg/m^2 at 4m size (THEIA)
- Passive mirror only
  - Very deep structure
- Testing in 1G to 0G specs is a challenge
- Multiple suppliers

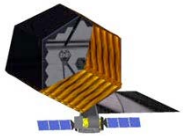


Lightweight ULE Segments



AMSD

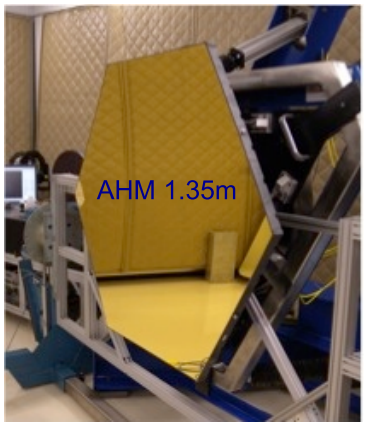
- Passive or active
- Evolved from traditional methods
- <10 nm rms SFE (projected)
- <5 Å microroughness (projected)
- <25 kg/m^2 total at 1.4m size
- If active:
  - Tens of actuators only
  - Likely to require a reaction structure
  - Actuators will require development
- Testing in 1G to 0G specs is a challenge

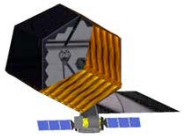


- **Low-expansion glass monoliths, when mirrors and structures are thermally controlled, have good UV/Optical WF stability**
  - 1-10nm RMS (WAG) depending on sun shielding and LOS pointing profile
- **ULE segments may have similar advantages, provided reaction structure and actuator thermal deformations are limited**

Mirror Technology: SiC Mirrors

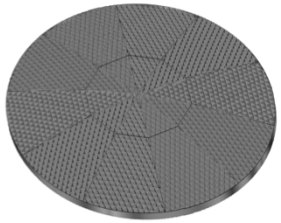
Actuated Hybrid Mirrors (AHMs)

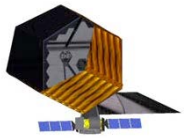


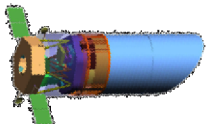


- 0.5 to 1.35 m size demonstrated
- <14 nm rms SFE demonstrated
- <10 Å microroughness (projected)
- 10-15 kg/m^2 substrate
- <25 kg/m^2 total at 1.4m
- Active mirror
  - 37 to 414 actuators
  - Solid state, integrated into SiC substrate
- Testable in 1G to 0G specs
- Made by replication

Polished SiC Mirrors







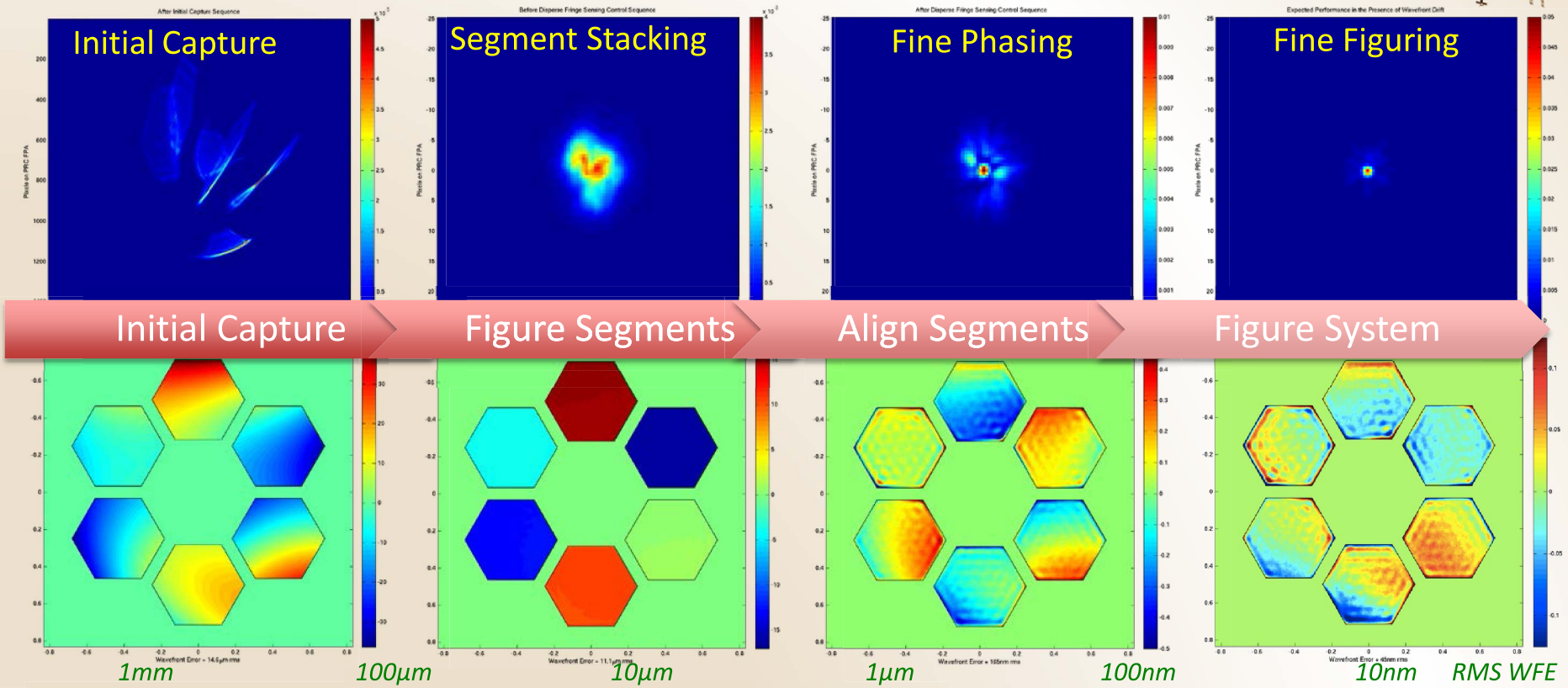
- Passive or active
- Made by casting, joining, cladding and polishing
- <10 nm rms SFE (projected)
- Cladding (Si or CVD SiC) enhances polishability
  - <5 Å uroughness (projected)
- <35 kg/m^2 total at 4m (projected)
- If active:
  - 0 to 10,000 actuators
  - Solid state, integrated into SiC substrate
- Active version is testable in 1G to 0G specs

- **SIC has good properties: 5x stiffer and 8x stronger than ULE**
- **SiC mirrors can be very stable if thermally controlled (1-10 nm RMS)**
  - High thermal diffusivity and open back structure
- **Polished Si Mirrors can be joined to make mirrors or segments to 4m**
  - Clad with Si (or CVD SiC), and then polished, for excellent surface quality
- **AHMs are made by replication, use Nanolaminate metal foil facesheets, provide an active option for mirrors up to 1.5 m**
- **Polished SiC mirrors can be used at cryogenic temperatures**

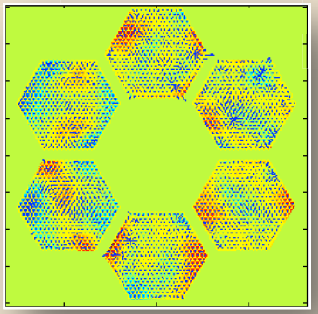
Mirror Technology: Graphite Mirrors

- Mirrors made with carbon or graphite composites (CFRP/GFRP) offer the promise of good stiffness and strength, low CTE, and fabrication by replication
- Multiple approaches are or have been under development
- Challenges remain, especially achieving needed figure quality and stability
- If these problems are solved, composite mirrors may provide the lowest-cost path forward for large segmented telescopes

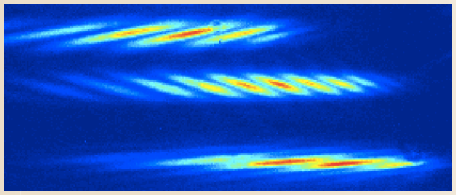
Wave Front Sensing and Control



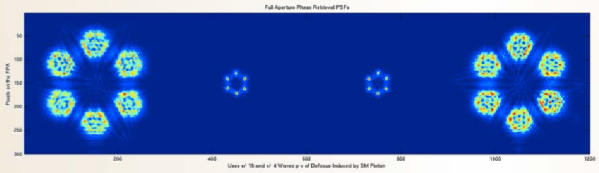
Shack-Hartman



Dispersed Fringe Sensing



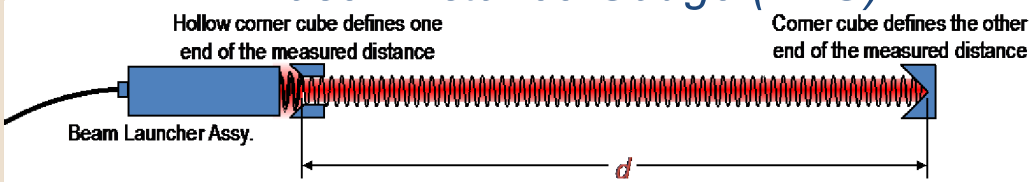
Phase Retrieval



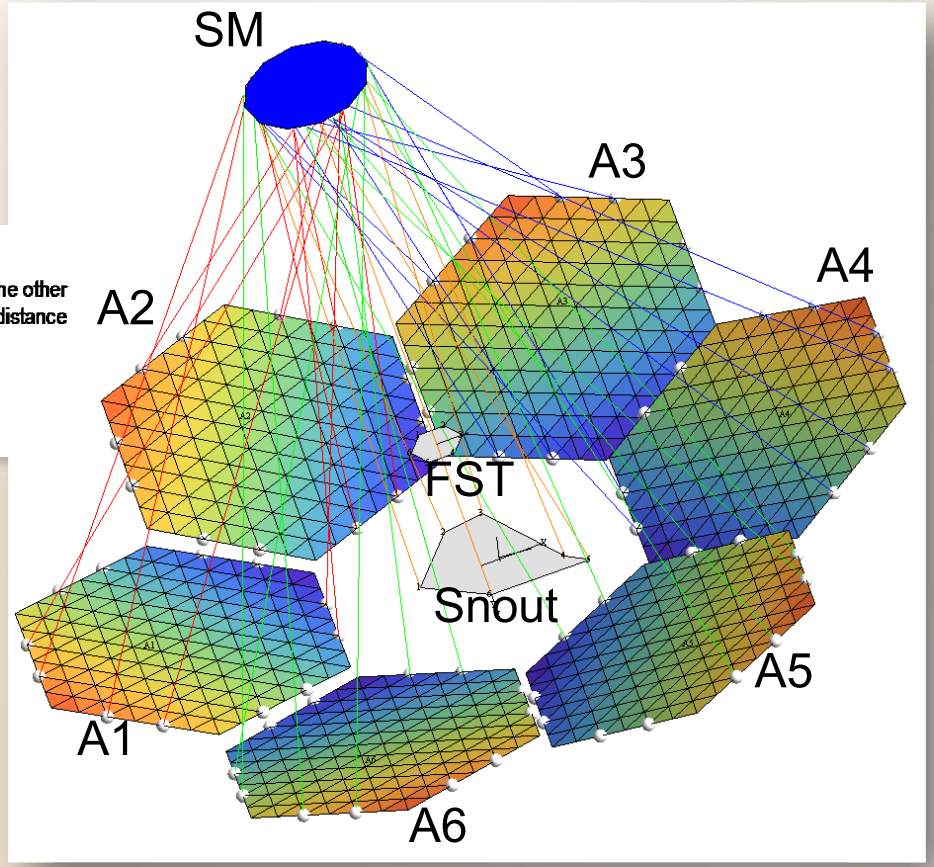
OPTIIX Laser Metrology

- WFS&C establishes the ideal alignment of the optics of the telescope…
- Laser Metrology-based control (MET) is used to *maintain* the ideal alignment in a changing thermal environment
  - MET monitors changes in the primary mirror segment and secondary mirror positions
  - Segment and SM Rigid-Body actuators continuously correct measured motions

A Laser Distance Gauge (LDG)

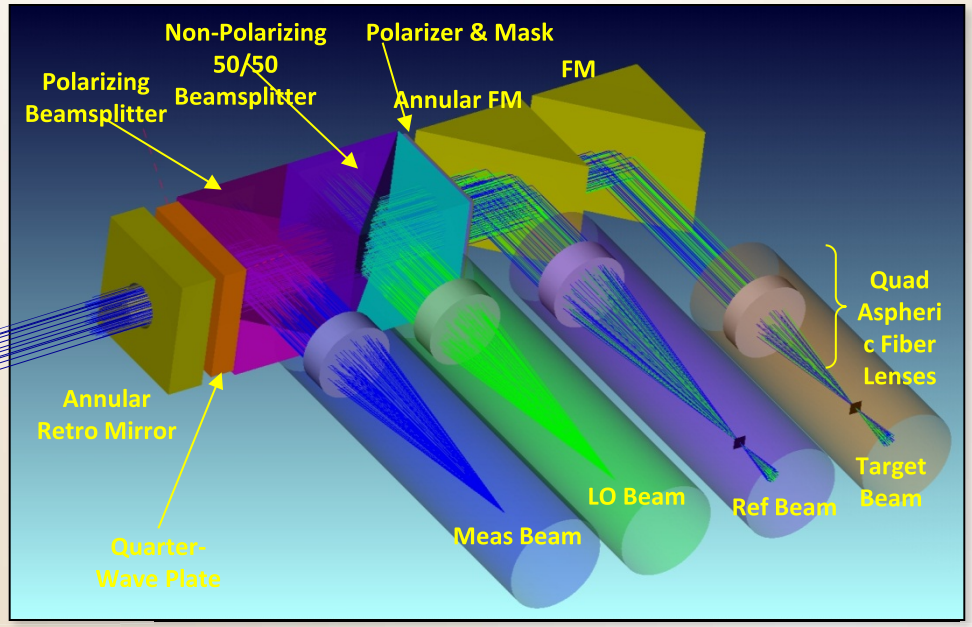


- MET uses a "Laser Truss" network of Laser Distance Gauges to measure each segment wrt the SM, and the SM wrt the "Snout" optical bench
- These measurements enable continuous alignment control with BW < 10 Hz and WFE < 20 nm (95%)

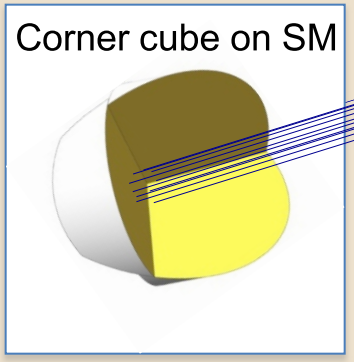


OPTIIX Laser Metrology

- Individual Laser Distance Gauges use CoPHI Common-path Heterodyne Interferometer developed by SIM project
  - Demonstrated precision < 50pm with low-cost, low-power elex

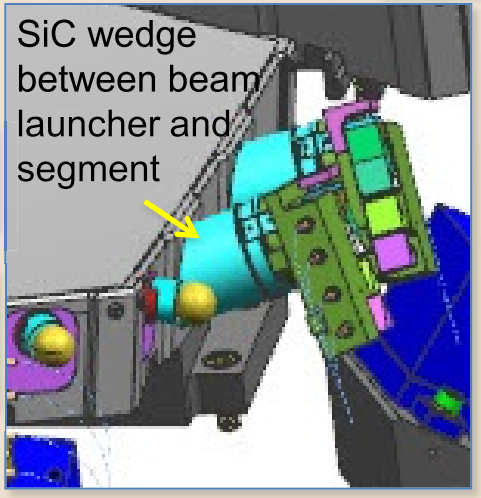


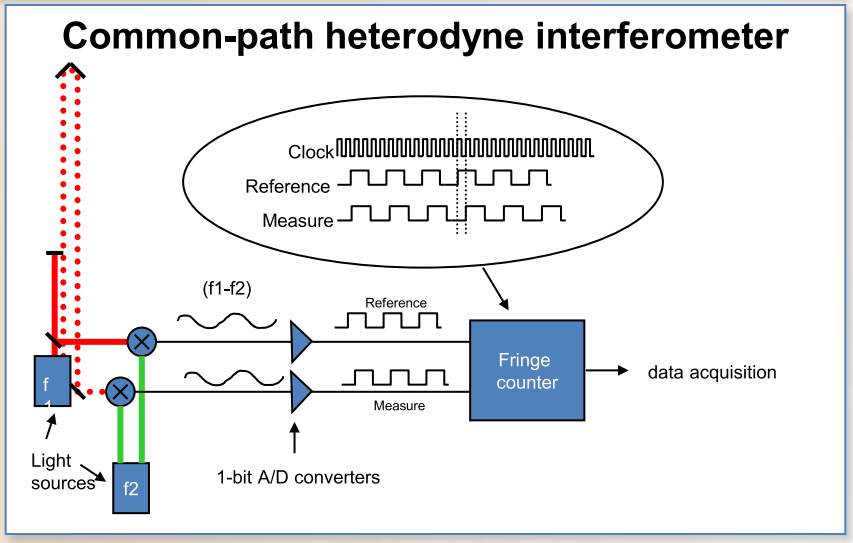
Corner cube on SM



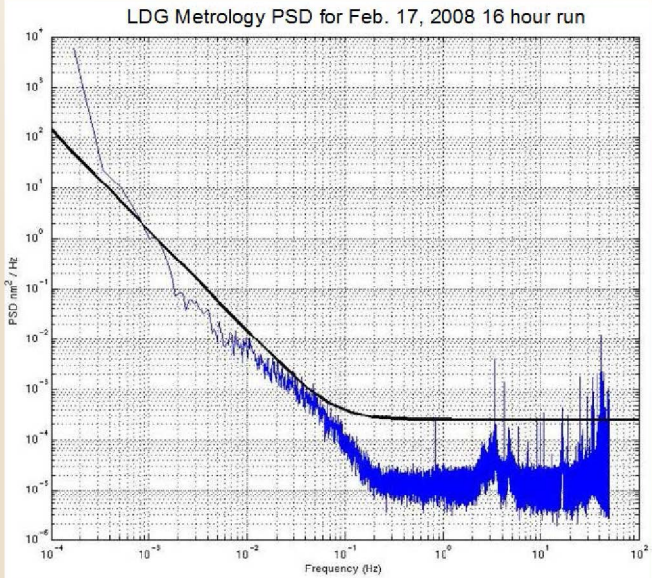
Metrology error multiplier
4.7nm rms WFE / nm rms

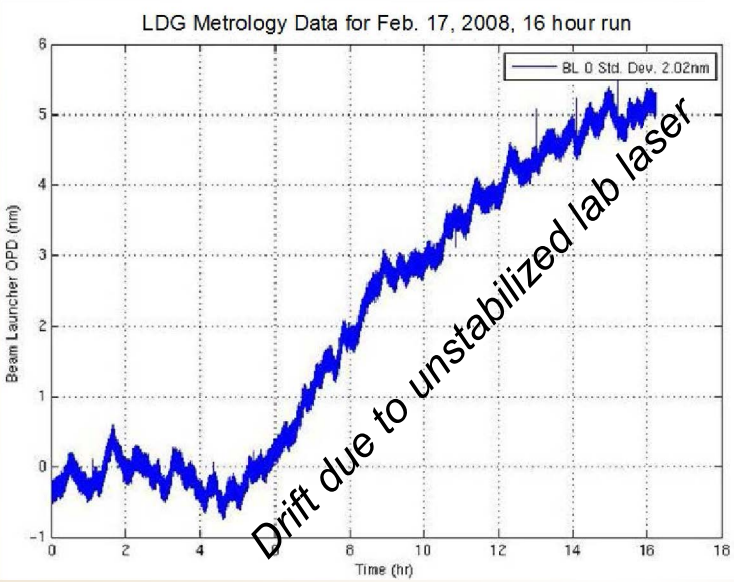
Segment temperature error multiplier
130nm rms WFE / K rms



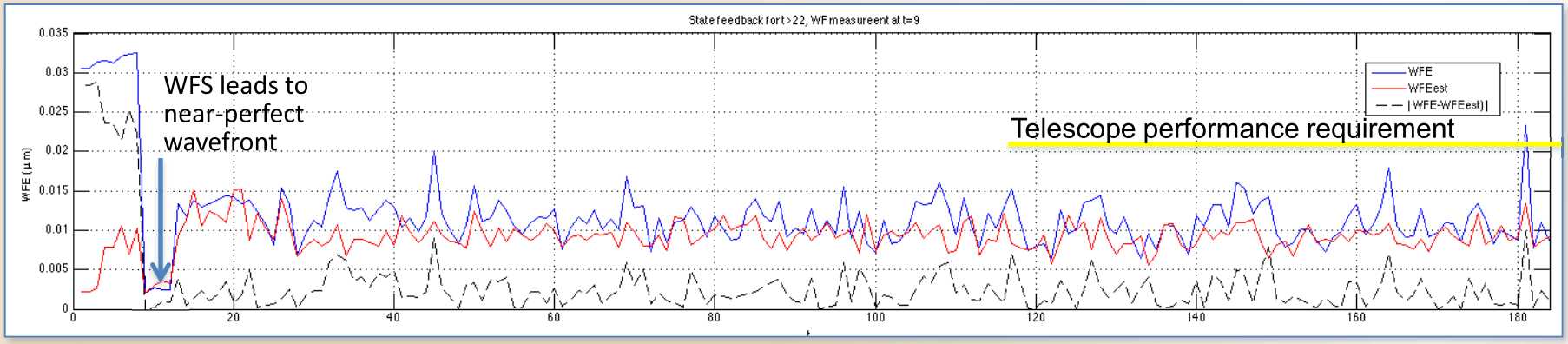


Metrology Performance





- LDG measured performance meets requirements



- Simulation of typical MET performance following a WFS&C update

Required Capabilities

Item	Needed Capability	Technical Approach	Current Capability	Development Needed
Primary Mirror Segments	Size ≤ 1.5m SFE < 8nm Mass < 20kg/m2 uroughness < 5Å ? actuators TRL 6 Low cost	ULE Segments with low CTE materials (mirror, reaction structure, actuators)	Size = 1.4m SFE < 10nm Mass < 25kg/m2 uroughness < 5Å 0-32 actuators TRL 4	Lower mass and cost; Space qualification
		AHM Segments with active thermal control	Size = 1.35m SFE < 8nm Mass < 25kg/m2 uroughness < 5Å 150-414 actuators TRL 6	Preserve manufacturing capability; Lower mass and cost; Minor technical improvements
		Polished SiC Segments with active thermal control	Size = 1.35m SFE < 8nm Mass < 25kg/m2 uroughness < 5Å 0-414 actuators TRL 3 at this size	Si cladding; Polishing lightweight substrate
		Composite segments	?	?
		Metal segments	?	?
Rigid-body actuators				
Metrology for OTA and Exoplanet Coronagraph control	Precision = 1 pm Sampling rate >1kHz Stability < 10pm/hr? BL mass < 200gm	Laser Truss	Precision < 1 nm Sampling rate >1kHz Stability < 1nm/hr? BL mass < 35gm TRL 6	Improve precision and stability
WFS&C…				

- **DRAFT table for group consideration…**

What do we need from other groups?

- **Concurrence…**
  - on aperture (8m, segmented)
  - on coatings, between UV and Coronagraph folks
- **Science requirements flowdown**
  - Will start with numbers derived from Postman's ATLAST talk
- **How much correction of WFE and WF drift is possible in a closed-loop coronagraph?**
  - Needed to set the OTA performance levels
- **What OTA sensing inputs are needed by the coronagraph?**
  - Metrology, encoders, WFS?

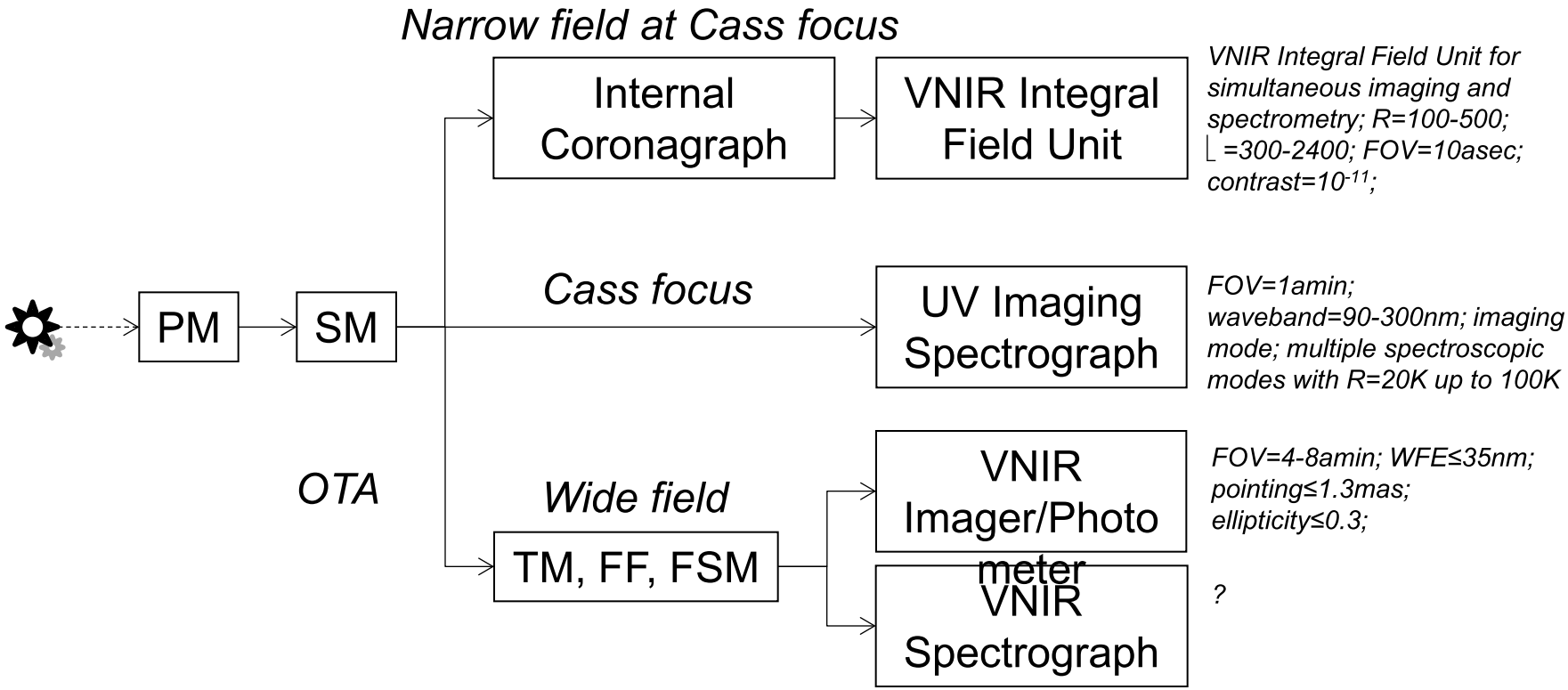
Backup

Key Science Requirements

			Measurement Requirements		Telescope		Instrument	Performance Requirements			Mission Requirements
	Science Goals	Science Objectives	Observables	Physical Parameters	OTA	Occulter		Measurement	Required Capability	Current Capability	
Driving Science Goals	"Is there another Earth out there?"	Search for the signature of life in spectra of >10 HZ XPs	Absorption lines of O2, H2O, methane in the planet spectrum	Bandpass = 300-2400nm;	WFE = 10nm; WFE stability	Internal Coronagraph or External Occulter	VNIR Integral Field Unit (IFU)	R=500 spectrum of an XP at 10 parsecs	Contrast = 1e-11; IWA = 40 mas; resolution=diffraction limited at 500nm; R=500		(ConOps)
		Land-sea ratio	Diurnal photometric variability					Disk-averaged, time-resolved photometric imaging	R=5; SNR≥20 for 5% Photometry		Precursor mission to ID targets
		Identify super-earths									Precursor mission to ID targets
		Search mode?						Imaging	High SNR		
		Mass loss from hot planets		UV spectra	UV coated PM and SM; instrument at Cassegrain focus	*Note: coatings may reduce coronagraph performance*	UV Imaging Spectrograph	Transit spectroscopy	High SNR		
	Establish a Comprehensive Theory of Star and Galaxy Formation	Sample resolved star populations in a broad range of galactic environments	Detect individual solar-type stars in at least 1 nearby giant elliptical galaxy	D up to 10 Mpc; Vmag≤34; Kmag≤35	Wide FOV=5-8amin; WFE<25nm; 1.3mas pointing stability	None	Widefield VNIR Imager/Photometer	4-8 arcmin FOV; SR>0.8@500nm; photometry SNR>5 at mag 34	4-8 arcmin FOV; SR>0.8@500nm; photometry SNR>5 at mag 34		
	Understand the Galaxy-IGM Interplay	Dissect the gaseous halos of the same local galaxy population	Absorption lines in IGM back-illuminated by QSOs	Observe ~10 QSOs behind all galaxies ≤10Mpc, and ~1 QSO to 30Mpc	UV coated PM and SM; instrument at Cassegrain focus; diffraction-limited at 500nm	*Note: UV coatings may reduce coronagraph performance*	UV Imaging Spectrograph		R=5K-40K; sensitivity to 90nm wavelengths		
			Emission spectra in IGM and resolved stars								
	Explore the Nature of Dark Matter	Map Dark Matter in the Local Group	Proper motions of the stars in Local Group dwarf galaxies		Wide FOV=5-8amin; WFE<25nm; 1.3mas pointing stability	None	Widefield VNIR Imager/Photometer	Astrometry	Star centroids to 0.1mas; centroid accuracy to 0.005% over 5 years; PSF ellipticity<0.3		
Key Science Goals	Spectroscopy of outer solar system planetary atmospheres (including moons of gas giants)						VNIR Imager, VNIR Spectrograph				
	High-resolution Imaging of asteroids and comets						VNIR Imager, VNIR Spectrograph				
	Build-up of chemical abundances in 1< z < 4 galaxies						VNIR Spectrograph				
	Masses of Active Galactic Nuclei and Super-massive Black Holes in z≤7 galaxies						VNIR Spectrograph				

- **Drawn from "Science Requirements for a 2030-era UVOIR Space Telescope," M. Postman, August 7, 2013.**

Instrumentation with an Internal Occulter



- **Instrumentation for an internal occulter (Coronagraph or Nuller)**

ATLAST Mass*

- **In the past, ATLAST studies have assumed a new heavy lift vehicle will be developed – relying on a new Delta IV fairing and improved mass, SLS, or Falcon Heavy with large fairing**
- **However, going into the 2020 decadal relying on a rocket that is not proven reliable (eg, minimum of 5-10 flights) could be risky**
  - Key concern is whether there is a large user base to drive development
- **Cost will be an issue**
  - Aerospace, Price H, ICE, and RAO cost models all use mass as a key variable
- **A quick look suggests:**
  - A 9.2m class observatory looks feasible using the Delta IV Heavy with some packaging changes; lower areal density can enable using the Ariane V.
  - A 14m aperture with lower areal density mirrors can work with the Delta IV Heavy mass but packaging will probably be the limiting item.
- **A lower areal density solution will both lower cost and enable missions that can be launched on existing rockets**
  - Smaller, lighter segments: ~20 kg/m^2 areal density
  - Glass, SiC and composite technologies offer performance and cost benefits

*From L. Feinberg, "Mirror Areal Density and Launch Vehicle Considerations for ATLAST," GSFC (2013).

Mirror Technology Priorities*

- **Lower areal density and lower cost and schedule mirrors**
  - 20 Kg per meter squared mirror segment assembly system solution (30% lower than JWST)
- **Architecture considerations**
  - Minimize mirror assembly and substructure
  - Optimize segment size
- **Mirror constraints**
  - Meet WFE budget, UV quality PSD (provide slope)
  - Thermal stability of 10 picometer per 15 minutes (interface?)
  - JWST acousto-vibro levels (20+G's), perform acoustic and vibe?
- **Multiple technologies**
  - Glass, SiC, composite approaches
- **A possible Mirror Technology development program?**

*From L. Feinberg, "Mirror Areal Density and Launch Vehicle Considerations for ATLAST," GSFC (2013).