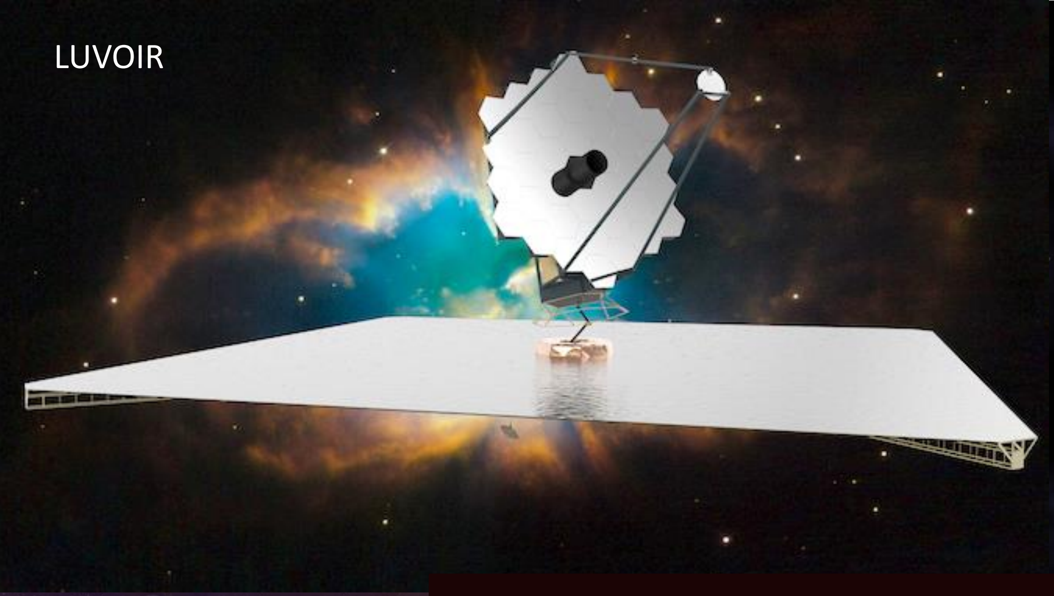
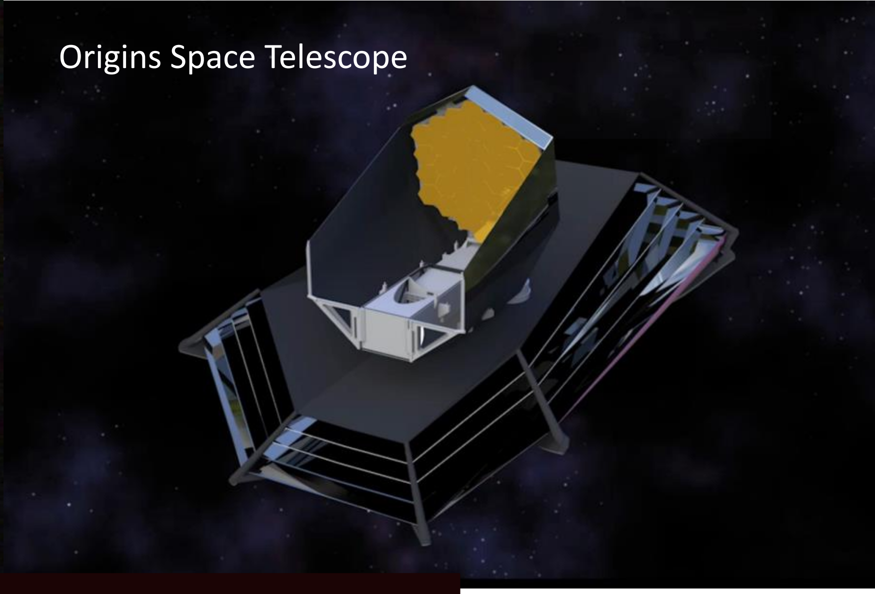
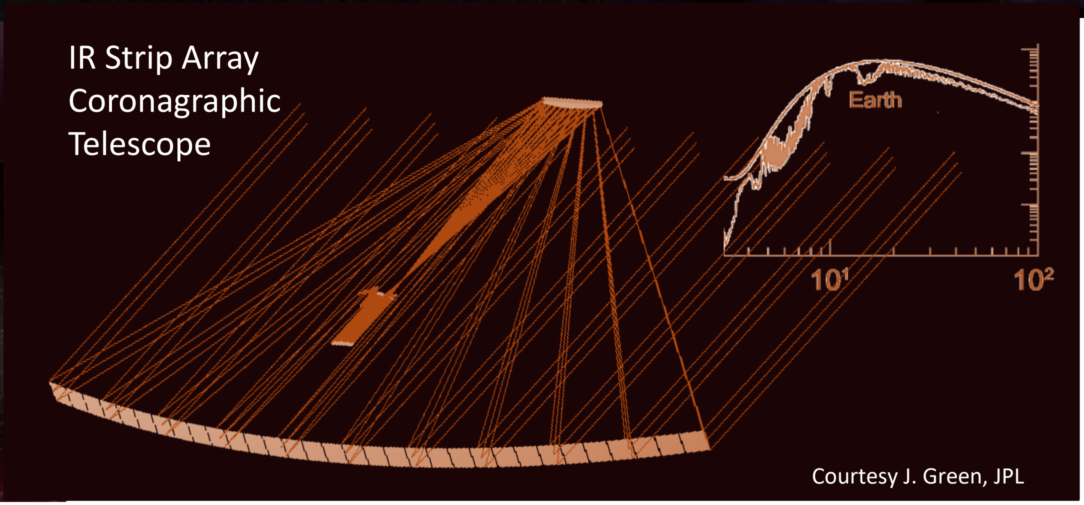
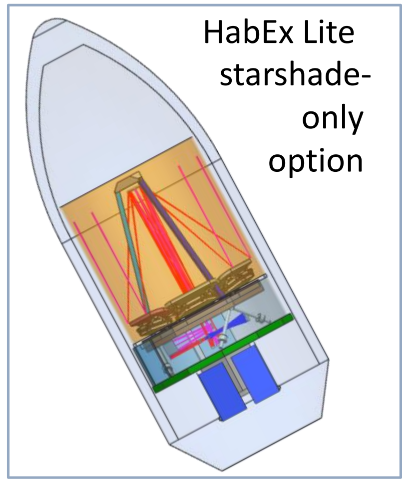








Workshop on Technology for Direct Detection and Characterization of Exoplanets

Large Segmented Apertures in Space

Active vs. Passive

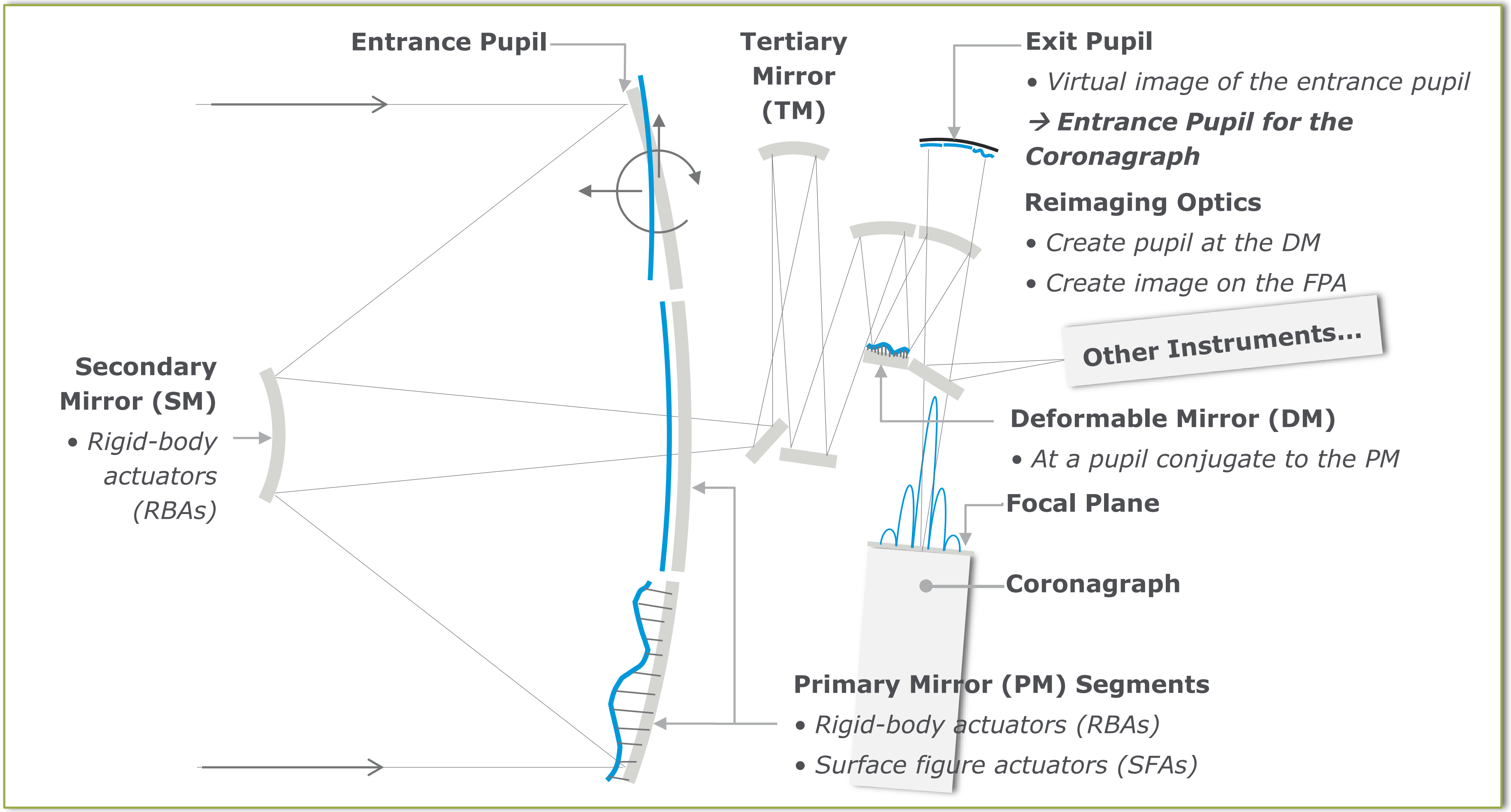
David Redding

Pre-Decisional Information -- For Planning and Discussion Purposes Only

Jet Propulsion Laboratory
California Institute of Technology

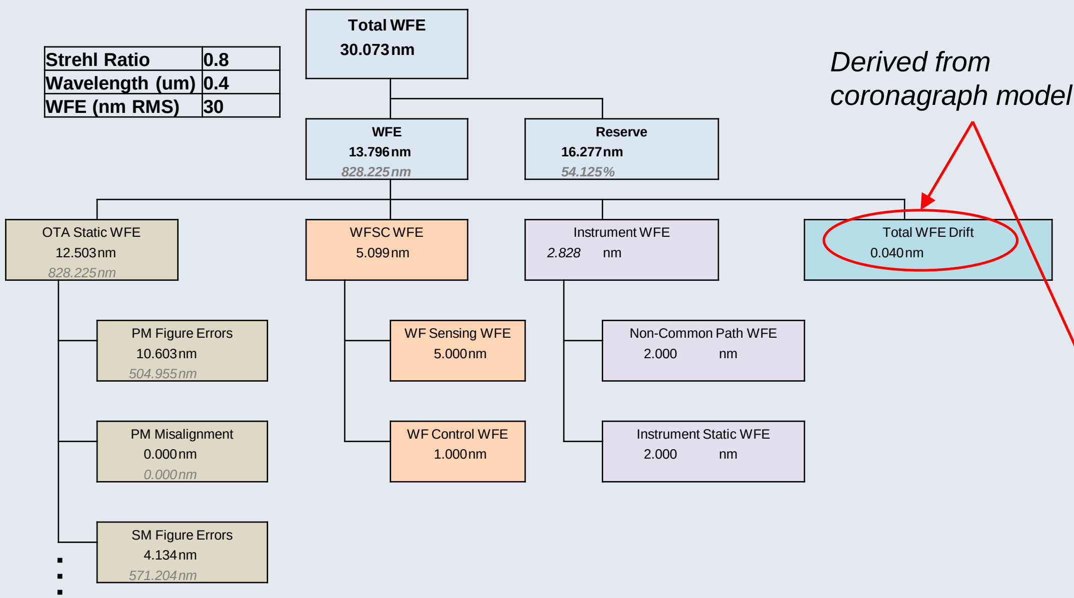
Segmented Space Telescopes

- All segmented telescopes are "active," with controlled PM segments and SM
  - Some will require: "active" (deformable) PM segments and/or DM
- Sensing elements include Science Cameras
  - Some will require: metrology (laser truss, edge sensors); dedicated WF sensor



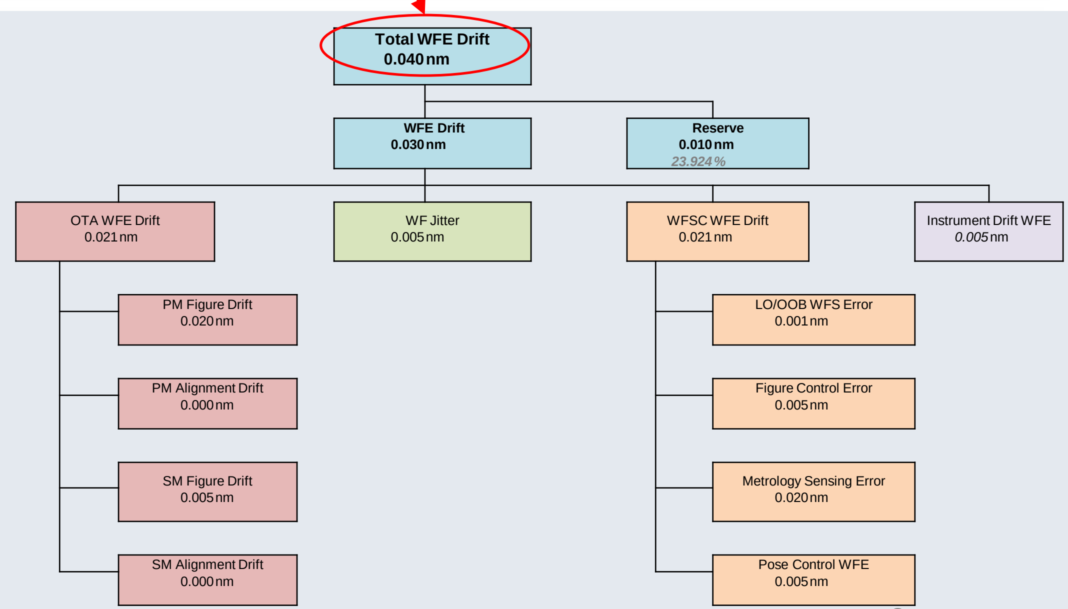
Notional Error Budgets: UVOIR

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



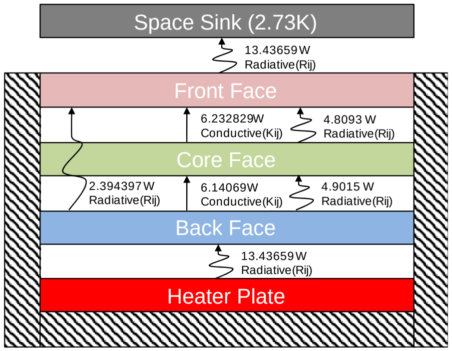
- Total Static WFE for a HabEx or LUVOIR is ~30 nm RMS
  - After initial WFSC
  - During all observations
  - With maintenance controls

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

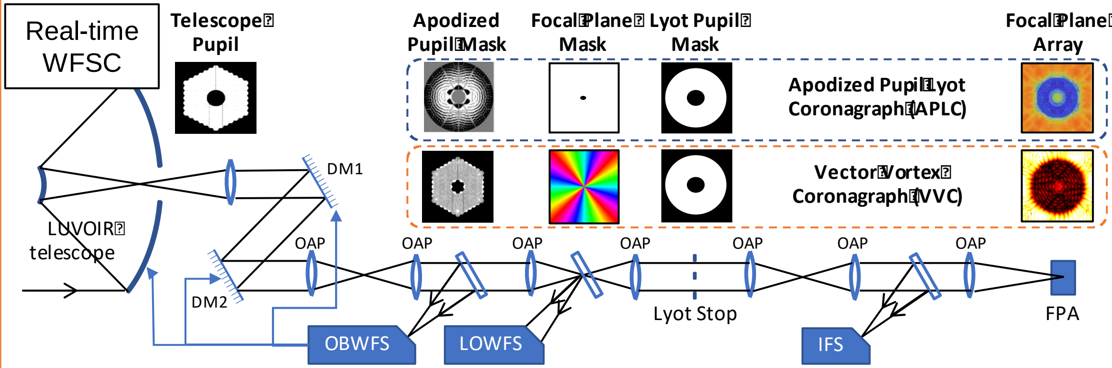


Active Control Methods for Ultra-Stability

Active Thermal Control

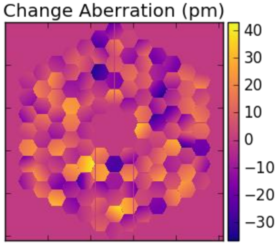


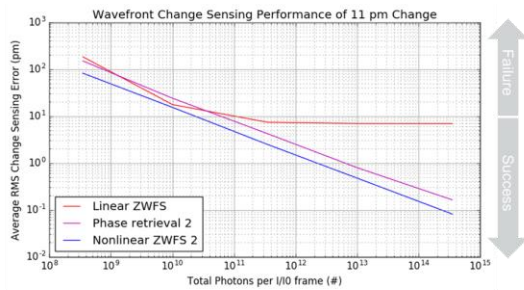
Real-time WFSC



Picometer WFS

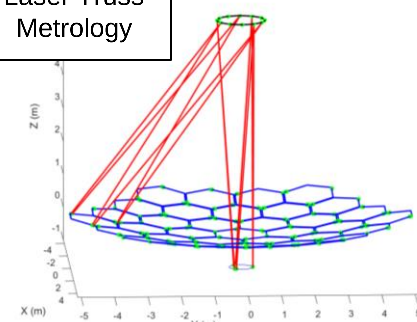
Change Aberration (pm)

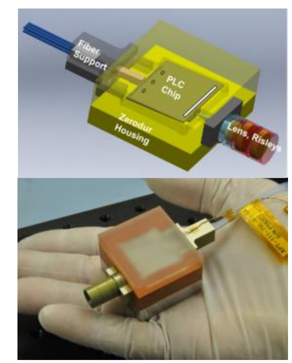




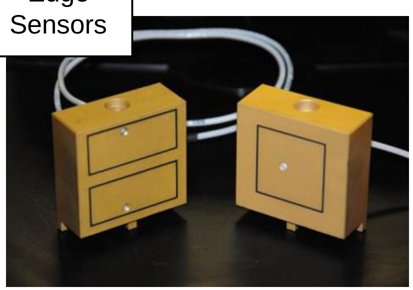
- $2x10^{10}$ photons available in 95 s exposure of 10^{th} magnitude star
  - Assuming B-band, 22% bandwidth, 135 m^2 aperture and *no losses*

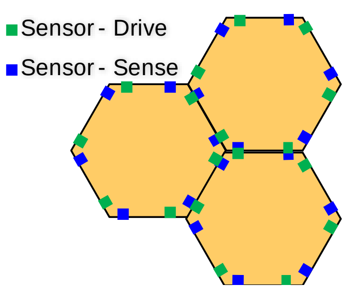
Laser Truss Metrology





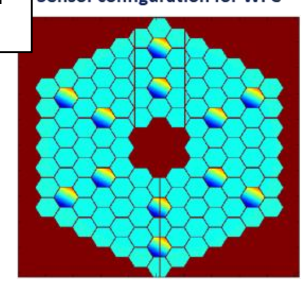
Edge Sensors





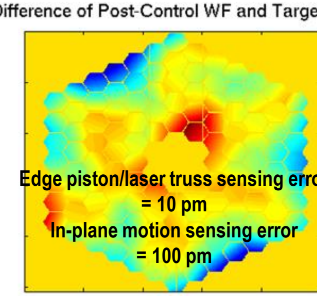
Combinations of techniques

Sensor configuration for WFC



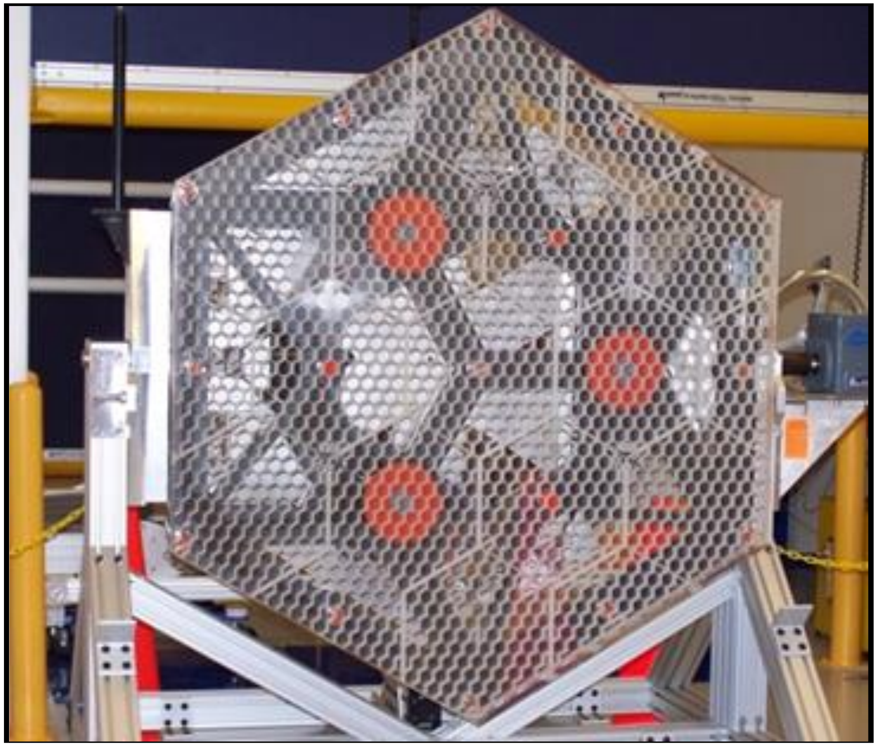
Edge sensing on all segments
Metrology on 12 segments, WEM = 2.99

Difference of Post-Control WF and Target WF



RMS =0.042948 nm

ULE Mirrors: Passive and Low-Authority Active

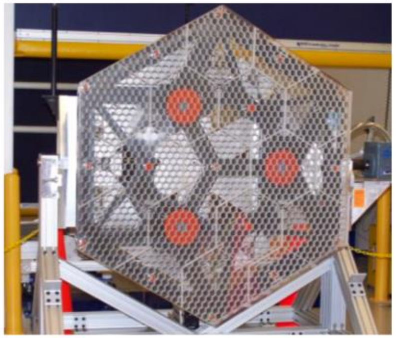


- ULE mirror segment technology. Harris (previously Kodak) has designed, fabricated and tested lightweight, passive and low-authority ULE segments. Harris has recently developed Capture Range Replication technology, enabling replication of mirrors to within capture range of final processes for figure and surface finish, eliminating much grinding and polishing. This technology is especially useful when multiple mirrors with the same prescription are needed, as is the case with segmented optical systems.

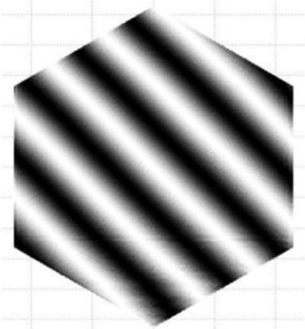
Demonstrations of ULE® Solution

HARRIS®

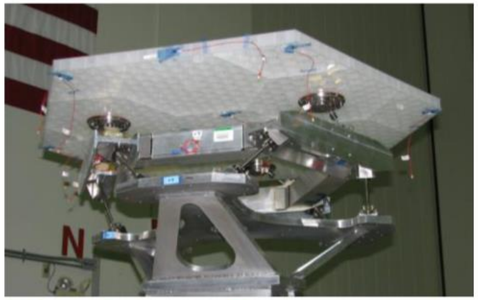
MMSD continued to drive the enhance the TRL level for future missions



A. OTM PMSA (Optical Test Model)
- Mirror is existing 1.4m AMSD mirror refinished for MMSD
- New MMSD mounts, actuators, reaction structure, elec, controls
- 0-G figure and figure control demonstrated via optical test with both 10 and 16 FCA configurations

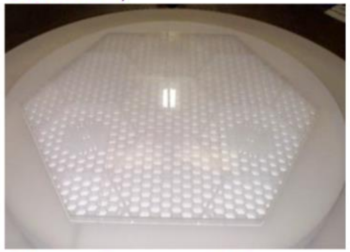


B. Mirror Segment B
- New full size MMSD mirror
- 0-G optical finishing demo
- Finished to 16 nm RMS WFE (no actuation)



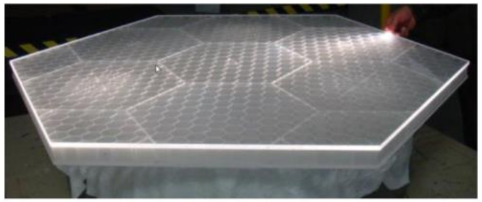
C. Mirror Segment C
- New full size MMSD mirror
- Finished thru LTS (100 um PV)
- Mounted & tested to high level random vibe & shock

Key validations achieved on each of these 10kg/m² mirrors



D. Mirror Segment D
- New full size MMSD mirror
- Completed thru plano fusion

Production rate on 3.5 week centers

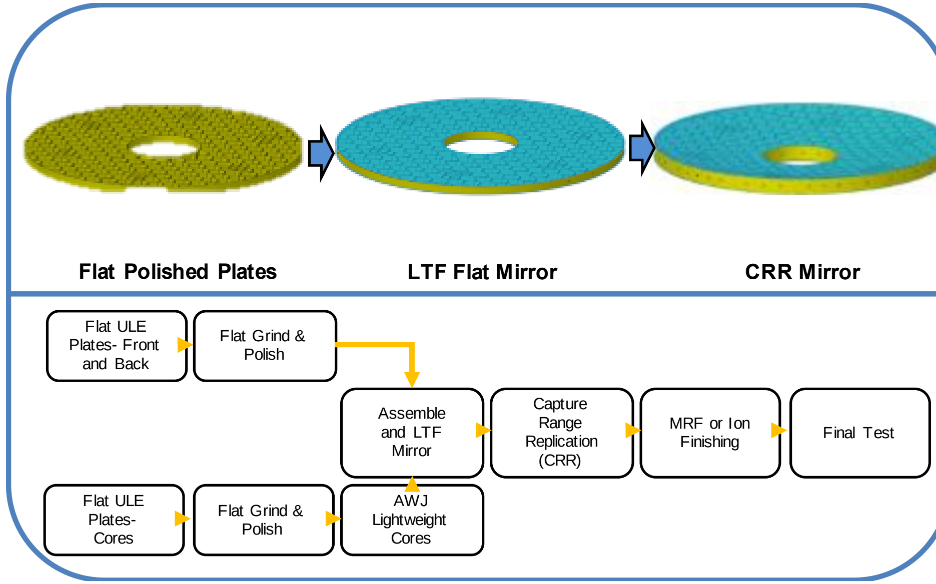


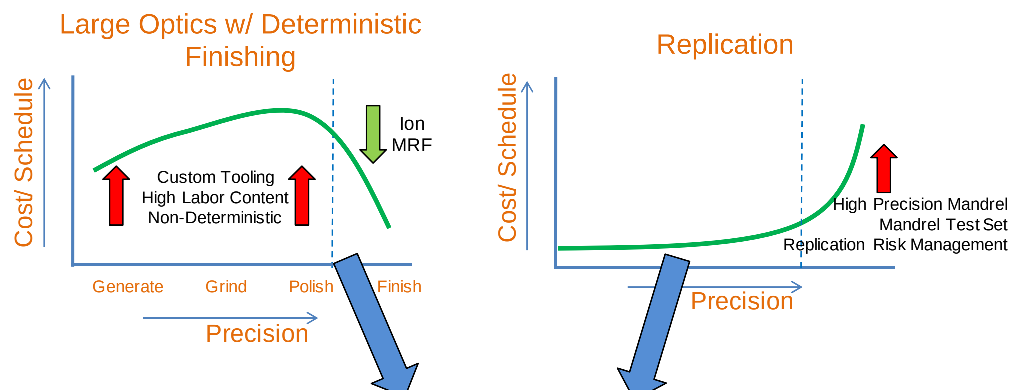
E. Mirror Segment E
- New full size MMSD mirror
- Completed thru plano fusion

https://asd.gsfc.nasa.gov/conferences/uvvis/flagship/UVVis_Flagship_Matthews.pdf

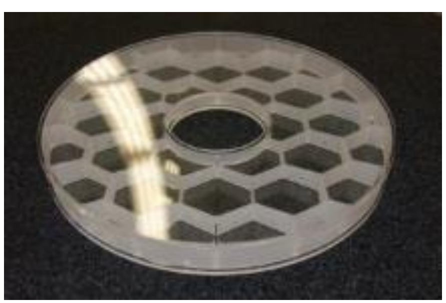
Harris Capture Range Replication

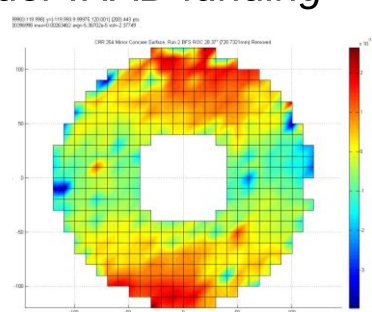
- Capture Range Replication uses precision mandrels and low-temperature slumping to replace traditional generate-grind-polish processes
- CRR finishes a mirror blank to within capture range for final finishing (MRF or Ion Beam)
- Result is a repeatable, efficient process for ULE mirror fabrication, saving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

ULE Mirrors: Passive and Low-Authority Active

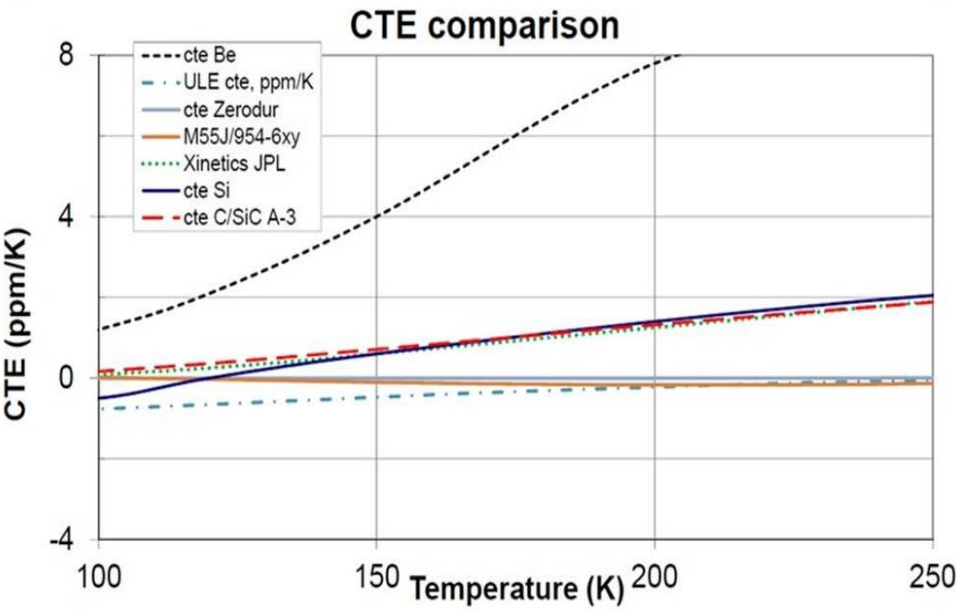
- AMSD and MMSD programs at Harris/Exelis/Kodak developed lightweight ULE mirror segments
- Further development has advanced manufacturability and lowered cost and schedule
- Low-authority architecture uses ~24 FCAs to compensate the most challenging fab errors
  - Meet 10 nm RMS figure error over full PM using current processes
- 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

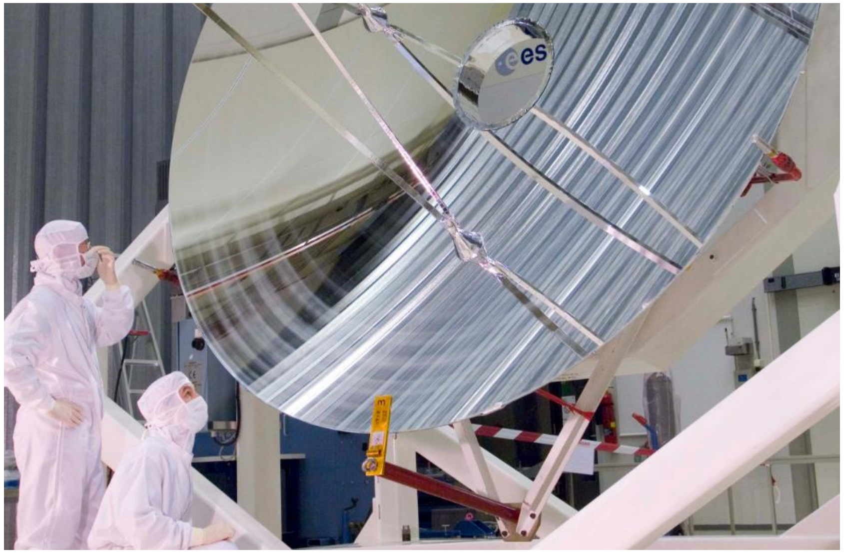
- Passive ULE segments meeting 10 nm RMS surface figure error may also be possible with further mfg. process development
  - To reduce ROC-matching errors
  - To improve 0-g figure prediction

Silicon Carbide (SiC) Mirrors

- SiC has many good properties
  - Stiff for the weight
  - Robust
  - High thermal conductivity
  - Polishable to <20Å (unclad), and to 2 Å (Si clad)

Property	Units	Aluminum	Beryllium	SiC	ULE	Desire
ρ, Weight	g/cm3	2.71	1.85	2.95	2.21	Low
E, Stiffness	GPa	68.3	303	364	67.6	High
E/ρ,Specific Stiffness	KN-m/g	25	164	123	31	High
σ/ρ, Stress Loading	N-m/g	46	11	24	3.2	High
α,Thermal Soaks	ppm/°C	22.7	11.4	3.38	±0.03	Low
Δα Homogeneity	ppb/°C	100	100	30	10	Low
K/α, Thermal Gradients	MW/m	6.9	19	51	44	High
K/rCp,Thermal Diffusivity	m2/s	6.55	6.07	8.7	0.08	High
K/αE, Thermal Stress	MW-m/N	101	63	140	646	High

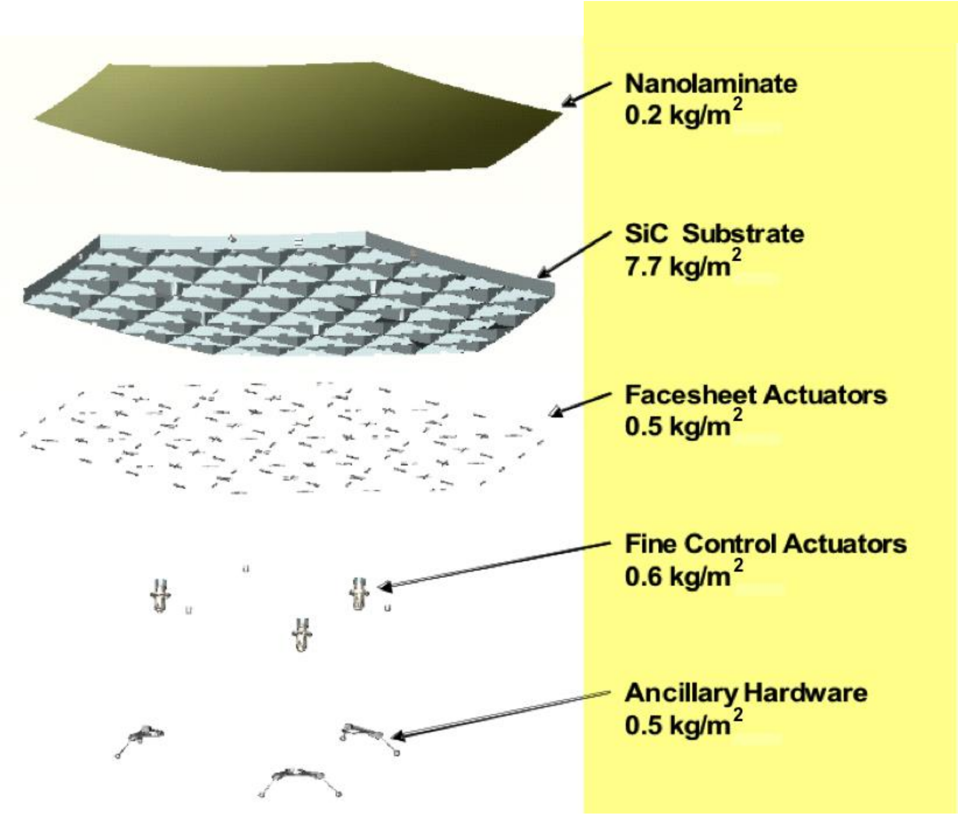




- The ESA Herschel 3.5 m Primary Mirror (PM)
  - Multiple segments joined by brazing

SiC-Based Actuated Hybrid Mirrors (AHMs)

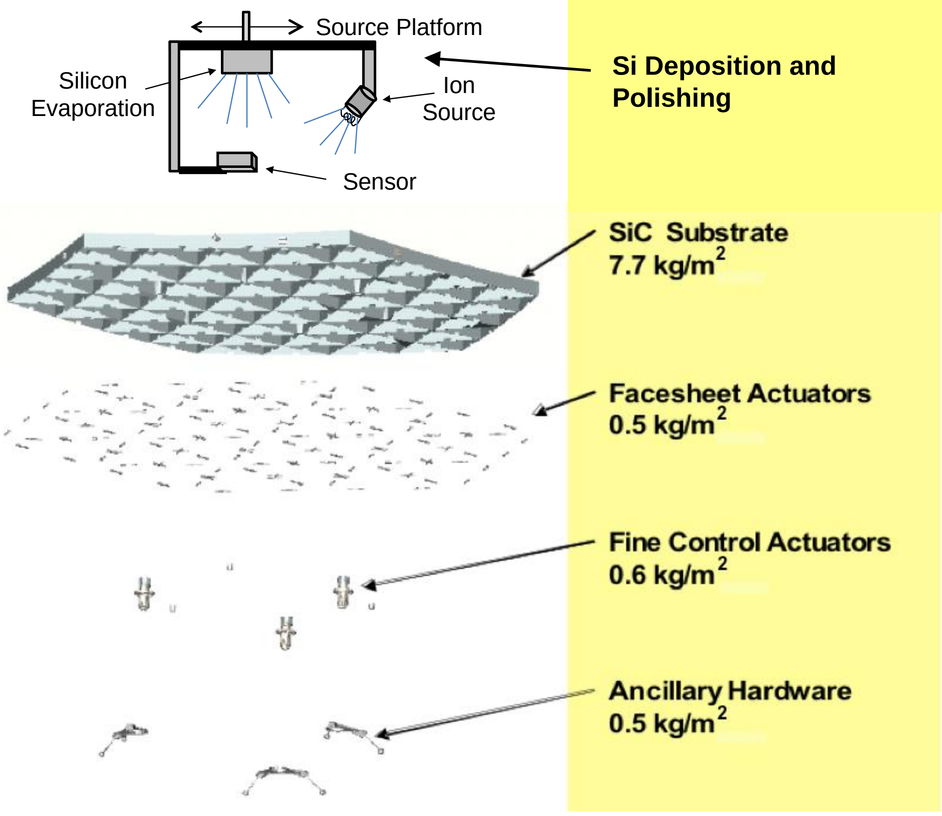
- AHMs are large mirrors
  - PMs or PM segments
  - Made by replication
- Nanolaminate facesheet
  - Multilayer metal foil, made by sputter deposition on a super-polished mandrel
- SiC substrate
  - Reaction-bonded Ceraform SiC is cast in a mold, fired, then bonded to facesheet
- Electroceramic actuators
  - Surface-parallel embedded actuators give large stroke and high accuracy, by design



- AHMs are low mass and high strength
  - Areal density < 25 kg/m^2 including electronics for meter-class AHMs
- AHMs are made by replication for high optical quality and low cost

Polished Active SiC Mirrors

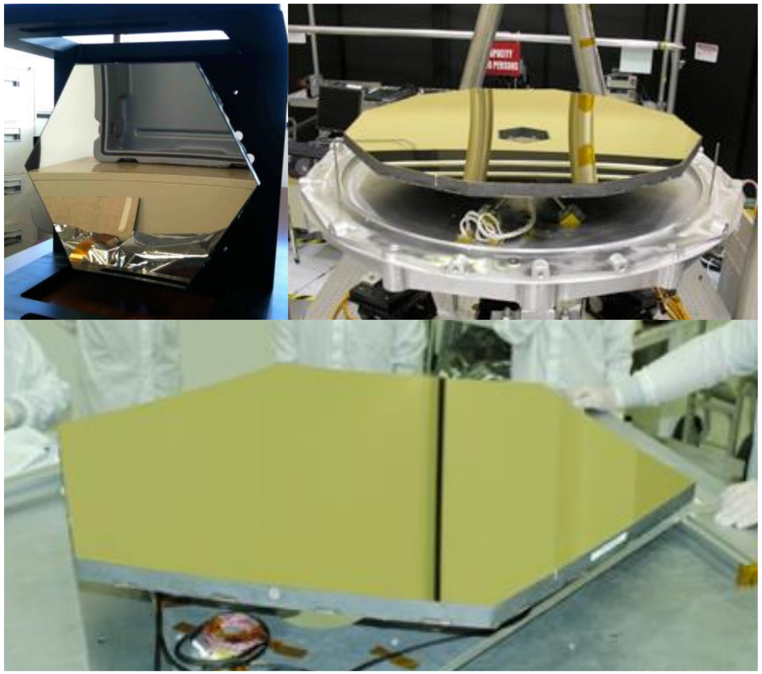
- Same SiC substrate
  - Cast to near-net shape, then rough ground
  - Large mirrors made by joining (brazing, e.g.) multiple segments
- Nanolaminate replaced by Silicon cladding
  - Low-stress Si deposited provides amorphous surface layer
  - Polishable to <5 Å microroughness
- Same facesheet actuators, mounts, and thermal control subsystems as AHMs



- Polished SiC mirrors are also low mass and high strength
  - Areal density < 25 kg/m^2 including electronics for meter-class mirrors
- Large SiC mirror

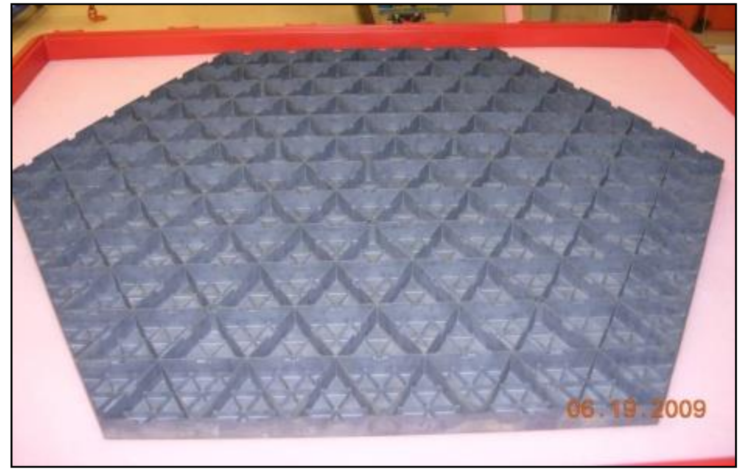
Actuated Hybrid Mirrors

Actuated Hybrid Mirrors (AHMs) provide an active mirror architecture

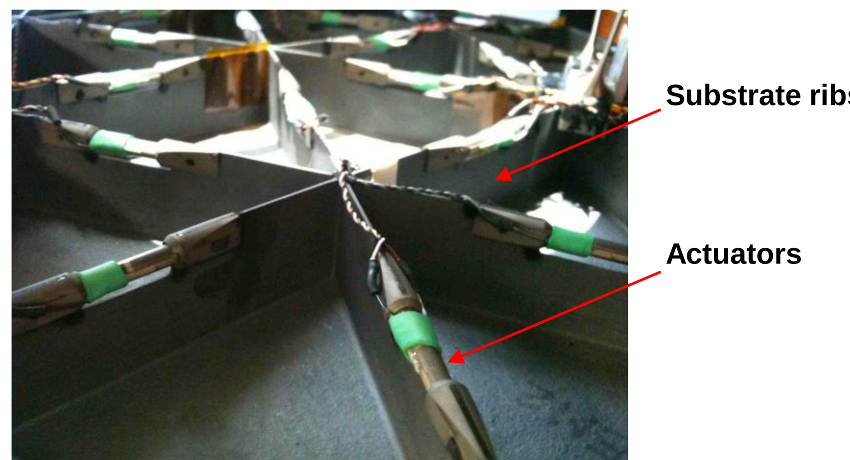


Unwin, S., et. al. (2010)

- Lightweight SiC substrates
  - 0.5 – 1.35m demonstrated
- Distributed surface-parallel actuation
  - 37 – 414 actuators demonstrated
- Replicated nanolaminate front surface



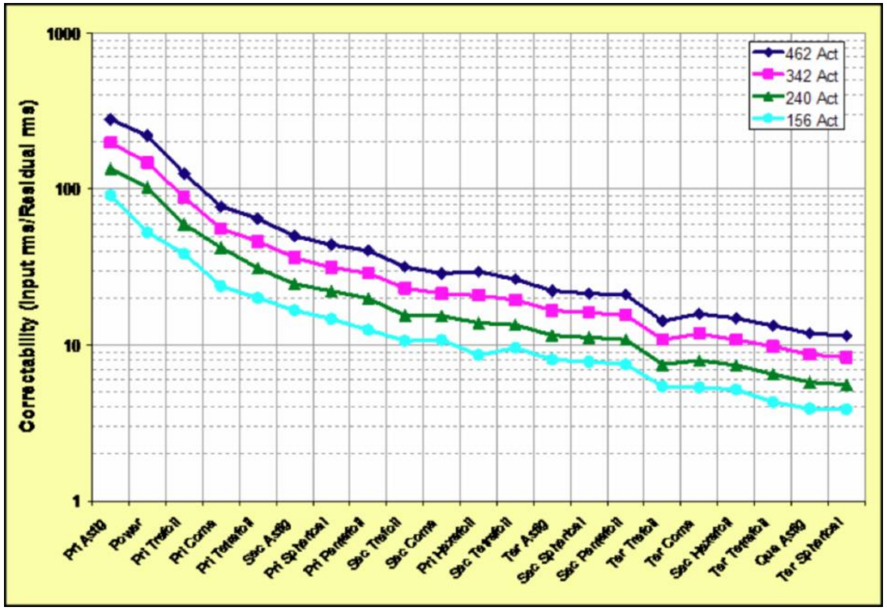
J. Wellman, G Weaver, D. Redding (2012), AAS Meeting 219-136.06



Unwin, S., et. al. (2010)

AHM Correctability

- Figure control performance:
  - <14 nm rms SFE demonstrated (dominated by initial figure error incurred during nanolaminate release)
  - High correctability over low-order modes
  - Tested in 1G to 0G specs
- Areal density:
  - 10-15 kg/m^2 substrate
  - < 25 kg/m^2 total



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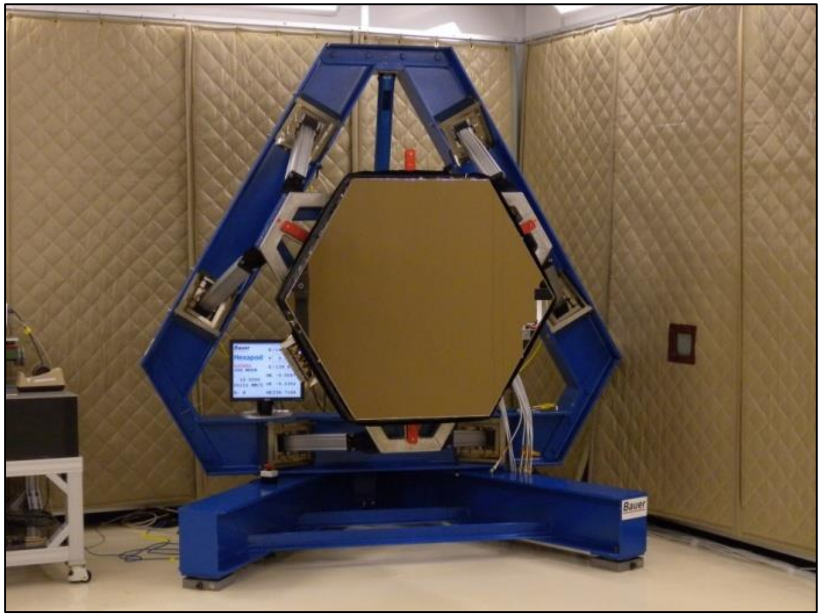
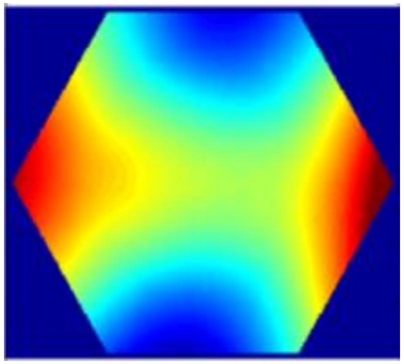
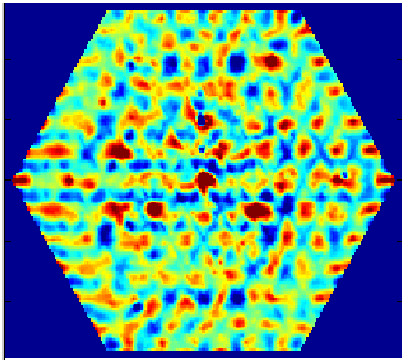


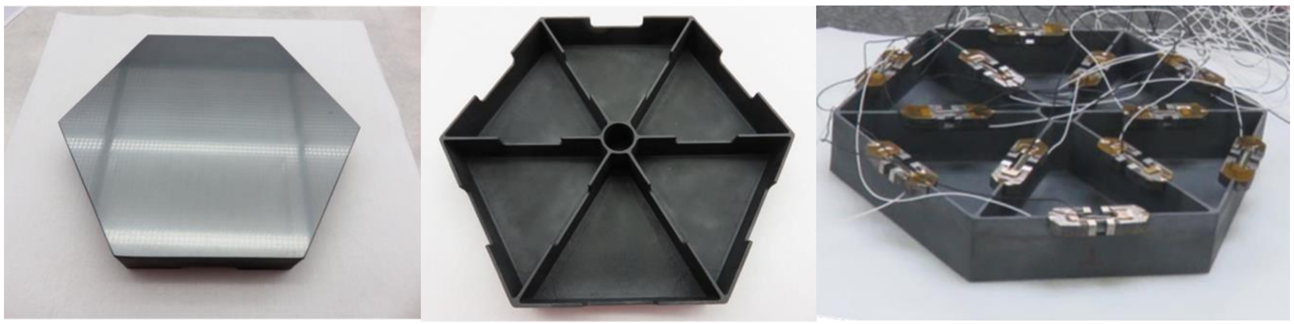


EM-4a Uncorrected
SFE = 1.88 µm RMS

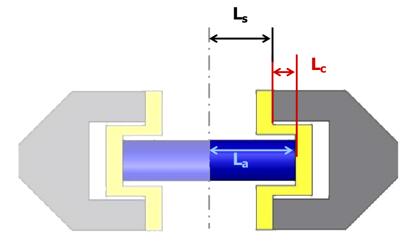


EM-4a Corrected
SFE = 0.014 µm RMS

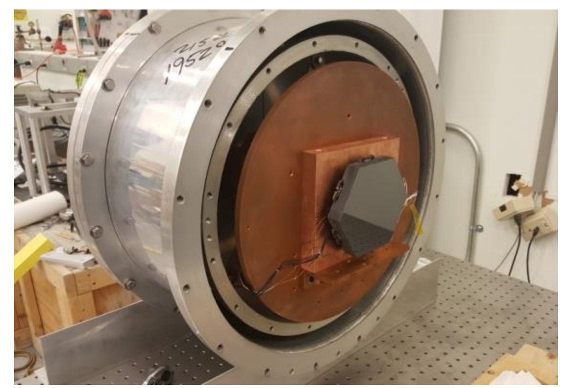
Cryogenic Active Mirror Demonstrator



"Athermalizing Clip"



- FY16 RTD Activity "Cryo Active Mirrors"
- Subscale active mirror built to demonstrate key functionalities at cryogenic temperatures
  - 0.15m dia, 12 PZT actuators, athermalizing clips
  - Direct polish of SiC
- Functionality characterized down to 26K in cryovac chamber
  - Demonstrated < 1µm RMS figure error at room and cryo temperatures

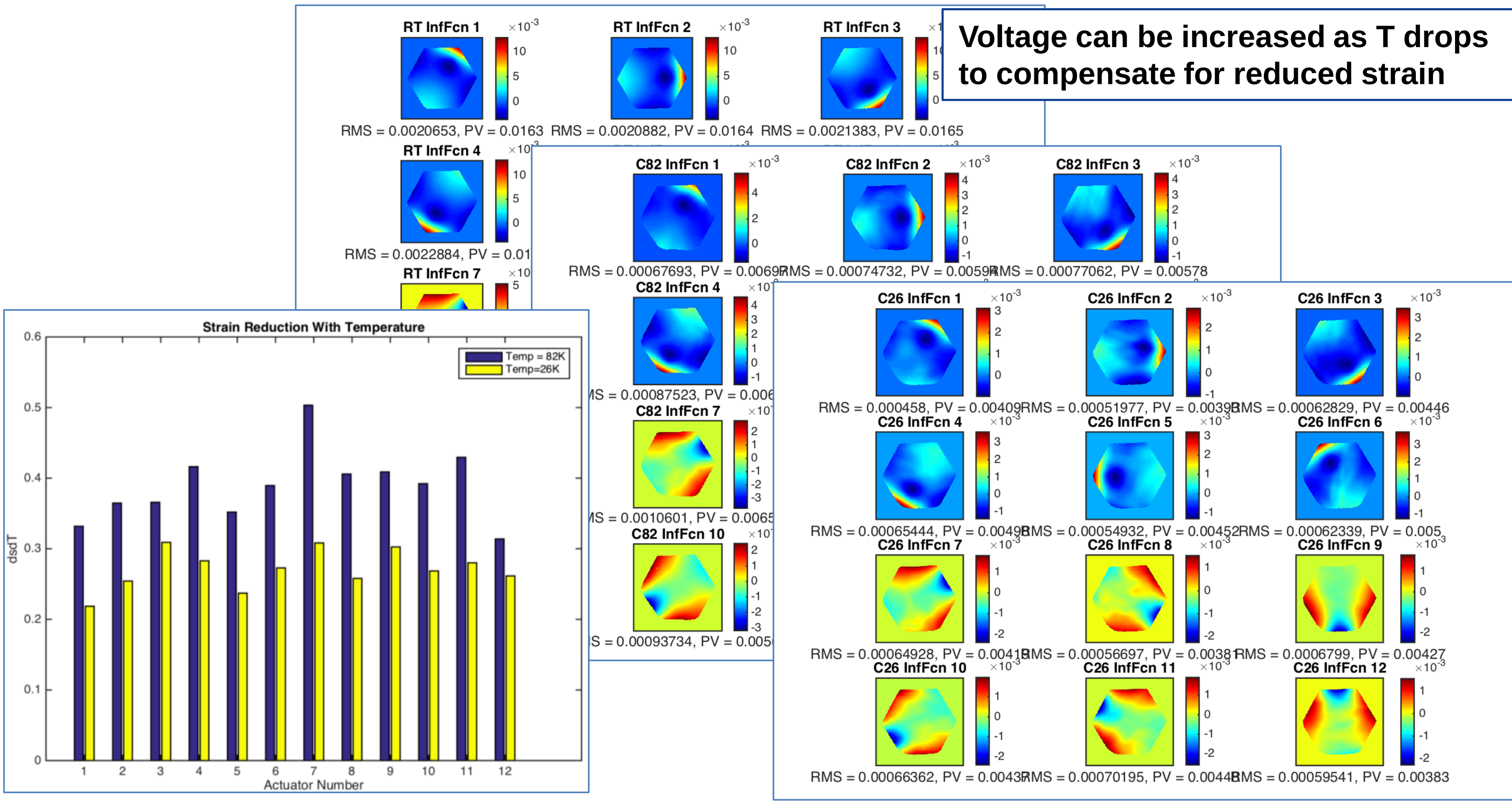


CAM established essentials for active mirror technology operating at cryo temps & FarIR wavelengths

Actuator Influence Functions

- Influence function measurements were made at 293K, 82K and 26K
- IFs showed consistent shape but reduced amplitude (per volt) as T drops
- Lowering the temperature reduces strain per volt
  - At 82K, reduction is 0.3895 = 1/2.57; at 26K, reduction is 0.2712 = 1/3.69

Voltage can be increased as T drops to compensate for reduced strain



Why Use Active Primary Mirrors?

- Segmentated mirrors:
  - To fit large apertures into small launch vehicles, using deployed apertures
  - To lower the mass of the entire space telescope, while preserving stiffness, for non-deployed apertures
  - To reduce risk associated with aggressive light-weighting of extremely large, brittle glass and ceramic structures
- Active mirrors, ULE or SiC:
  - To enable large apertures within current manufacturing capabilities
  - To prevent mission degradation or failure due to fabrication and/or testing errors
  - For testability in 1g
  - To lower mission costs:
    - By relaxing tolerances for many optical specifications throughout the observatory
    - By reducing thermal control power requirements
    - By speeding assembly and test
- Highly-active SiC mirrors:
  - For high optical quality at any temperature without cryo-null figuring
    - For testing at room temperature and operation at cold or cryo temperature
  - To provide high actuator density to support high contrast imaging

Backup

Highly Active PM for Coronagraphy

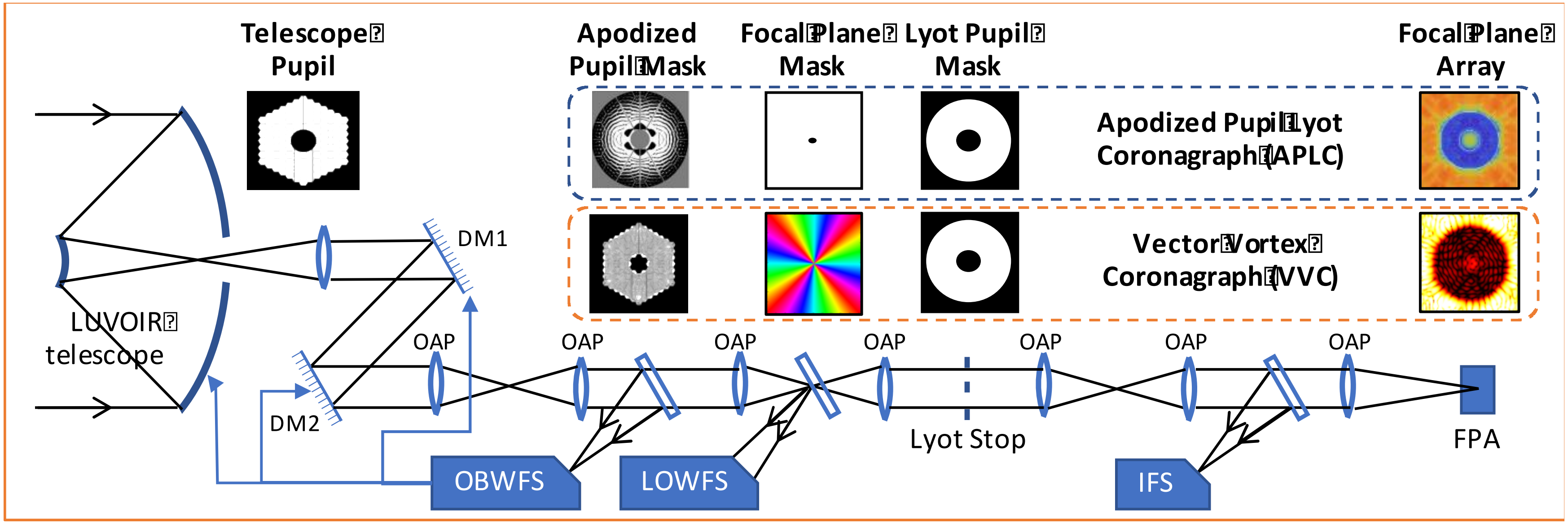
- Active SiC mirrors have the potential to...
  - Provide diffraction-limited wavefront quality – in the EUV
    - < 1 nm SFE and < 2Å microroughness
    - On orbit, at operating temperature
    - On the ground, for system testing in 1G, at room temperature
  - Remove 1 Deformable Mirror from the coronagraph
    - And any relay mirrors, for fewer aberration sources, less scatter, and higher throughput
  - Provide high actuator density, for a wide dark hole
    - >240x240 actuators across an 8 m aperture, if desired
  - Eliminate the largest WF errors at the source, for segmented or monolithic PMs
- SiC mirrors are stronger and lighter weight than glass, potentially leading to lower mission cost
- But what about thermal stability...?

Requirements Drive Telescope Architecture...

and High Contrast Imaging (HCI) method drives requirements

- Resolution, sensitivity, Inner Working Angle (IWA), and ExoEarth Yield drive aperture size
  - UVOIR
- General Astrophysics (GA) image quality sets Telescope Wavefront Error (WFE)
  - Diffraction limited at 400 nm (30 nm RMS) for GA and Starshade
  - Same at *input* to Coronagraph
    - Then Coronagraph uses DMs to shape WFs to <10 pm precision
- WFE stability requirements differ between Starshade and Coronagraphic telescopes
  - ~10 nm RMS for GA and Starshade-only telescopes
  - ~10 pm RMS for Coronagraphic telescope: *Ultra-Stability*

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...

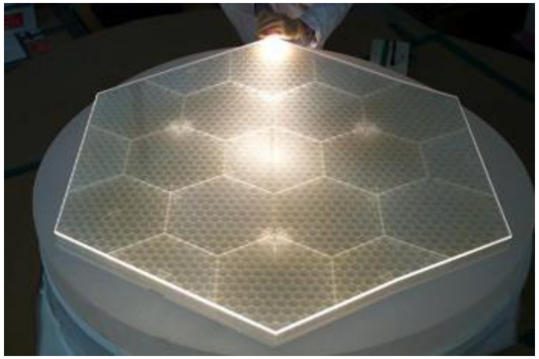
Coronagraphic Telescope Architecture Options

ULE 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	ULE, 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	Zerodur, 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

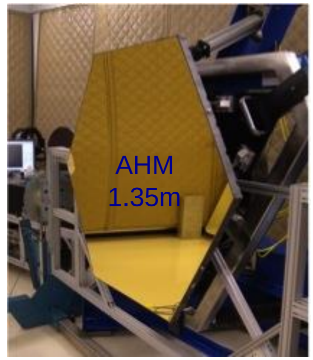
SiC Architecture Options										
Instruments	**Aperture**	**Temperature**	**PM Mirrors**	**Mirror Thermal**	**Figure Actuation**	**Stabilization**	**Metrology**	**Sensing**	**Pointing Control**	**System-Level Testing**
Coronagraph	Monolithic	Heated to room temperature	ULE, closed-back	Stable material, 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	Zerodur, 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

- Other considerations include coronagraphic performance (gaps/segment edges/corners)

Mirror Technology



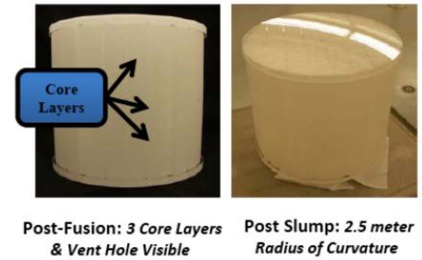
MMSD Lightweight ULE Segment Substrate



AHM SiC-based Segment Substrate

- **Primary mirror segment technologies have been developed at the needed (1.2-1.4m) size by NASA and other agencies**
  - ULE glass and SiC-based designs offer alternatives
    - Ultra-low expansion glass is difficult to control thermally
    - SiC has higher expansion, but is much more controllable
  - Both are lower cost and faster to make than JWST Beryllium mirrors
- **Further development is needed for ATLAST**
  - Complete and test mirror *systems*, including UV quality, actuation and thermal control

HST Primary



AMTD deep-core mirror technology for large space mirrors

Subaru Telescope meniscus primary mirror, 8.2m diameter, 23,000kg mass, showing some of its 261 actuators

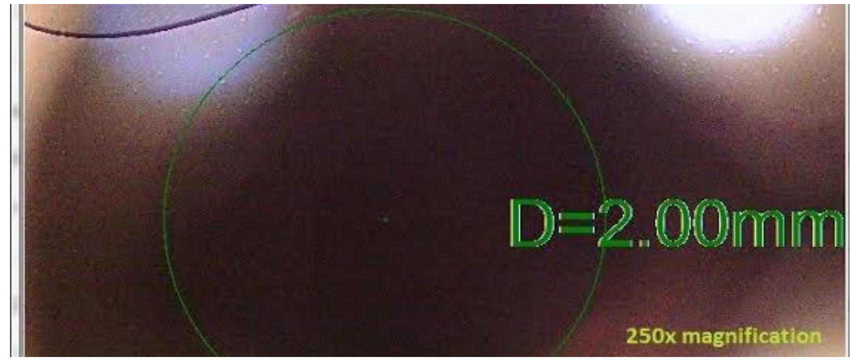
- **ULE monolithic primary mirror technologies are mature for space at the 2.4m size**
- **Growth to 4m or larger requires development**
  - AMTD: technology development for large lightweight mirror substrates, funded by ROSES SAT
    - Need to address mirror *systems*, including thermal control
  - Meniscus mirrors: not yet developed for space, but in use on the ground

- **Recommendations:**
  - Perform modeling and analysis to quantify mirror system performance, stability, mass, cost and fabrication issues
  - Initiate UVOIR segmented mirror development program, in parallel with AMTD monolithic mirror program, to validate models and demonstrate technology readiness for mirror systems

ZeCoat Si Cladding Performance

Before polish:

After polish:



Surface Quality		Before Polish		After Polish	
		RMS (A)	PTV (A)	RMS (A)	PTV (A)
6 months ago	high rate	17	302.4	0.86	7.13
	low rate	11.5	142.5	1.45	8.9
recent	high rate	4.2	80.1	1.46	8.63

Stress	thickness (microns)	Stress (Mpa)	rate (A/sec)
run 3	25	18	50
run 4	27	53	50
run 6	28	51	50

From ZeCoat SBIR progress reports, and mirror inspection discussion:

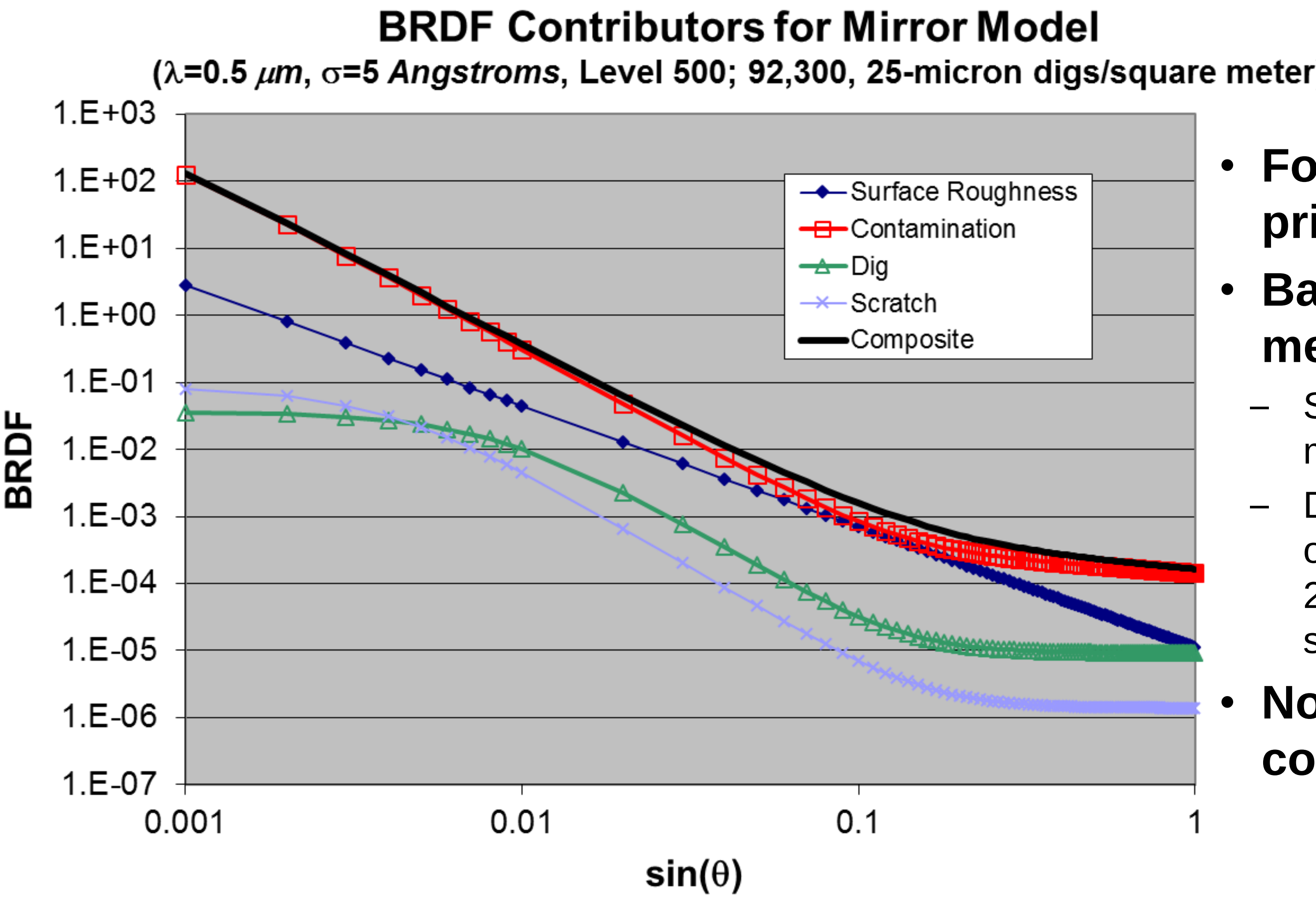
Low-Stress Silicon Cladding for Surface Finishing Large UVOIR Mirrors

Mirror Inspection Discussion

SBIR Phase II Contract No. NNX14CP14C
David Sheikh, Principle Investigator
David Redding (JPL), Technical Monitor

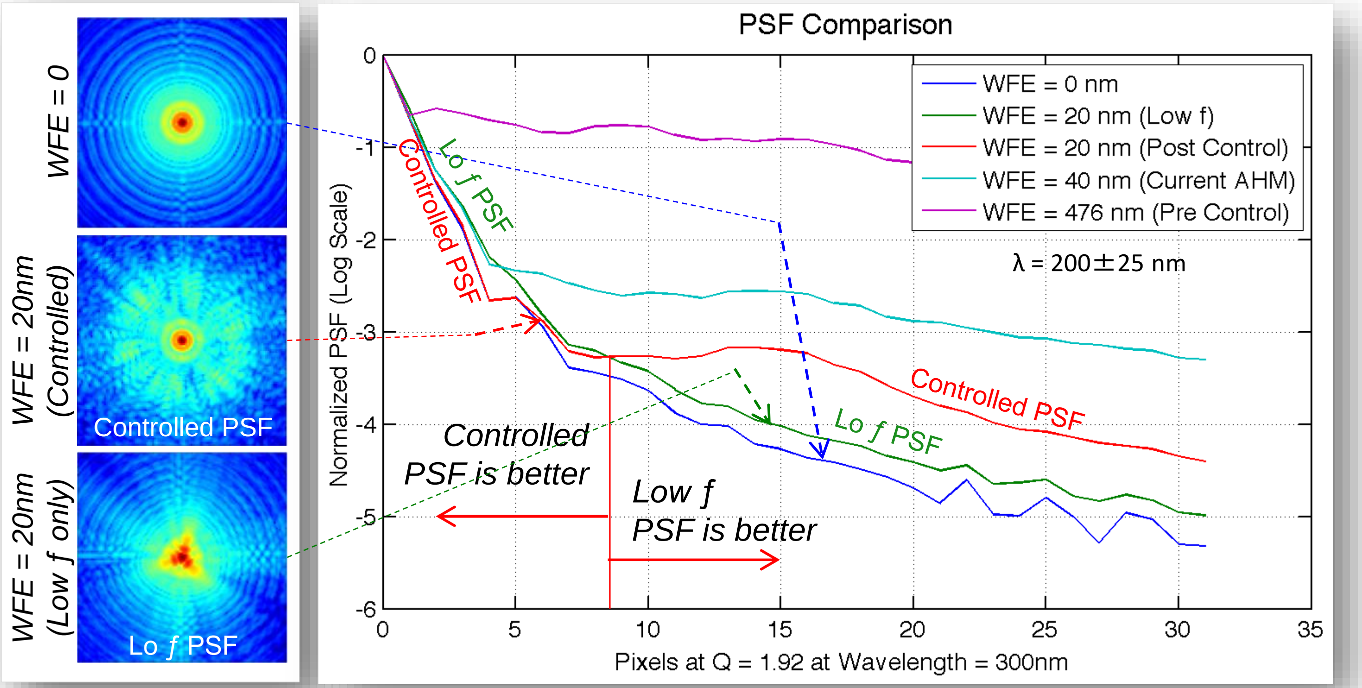
ZeCoat Corporation
Torrance, California
3/30/16

Preliminary BRDF for Si-clad SiC



- **For a 10 m primary mirror**
- **Based on ZeCoat measurements**
  - Scratch = #1 (10 micron width)
  - Dig density observed: 92,300 20-um defects per square meter
- **No reflective coating**

Active Mirror PSFs



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

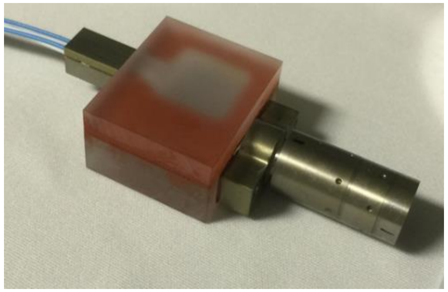
- Nominal WFE = 20nm
- Detector is critically sampled at λ = 300nm
- 400 actuators for control case

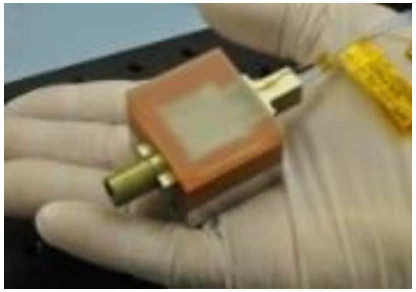
- AHMs and active SSMs, like Deformable Mirrors generally, have a different distribution of WFE vs. *ƒ* than conventional optics
  - Lower error in the low spatial frequencies
  - Higher error at and beyond the actuator spatial frequency
- This results in a tighter PSF core, but a raised "halo" in the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

Metrology Capabilities

- Beam launcher utilizes integrated optics for compact form, light weight, and high performance

PLC* beam launcher





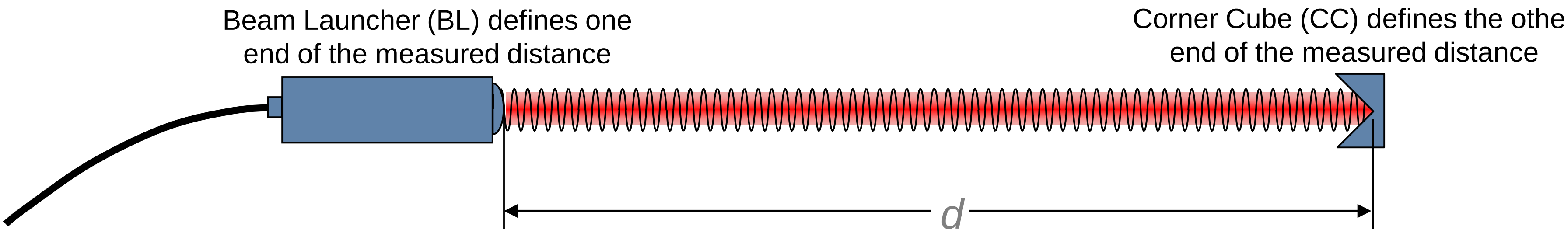
*PLC -- planar light-wave circuit
Silica-on-silicon waveguide technology

Courtesy F. Zhao, A. Azizi, et al (2015)

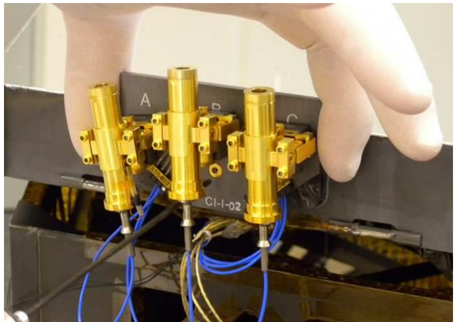
Performance Capabilities

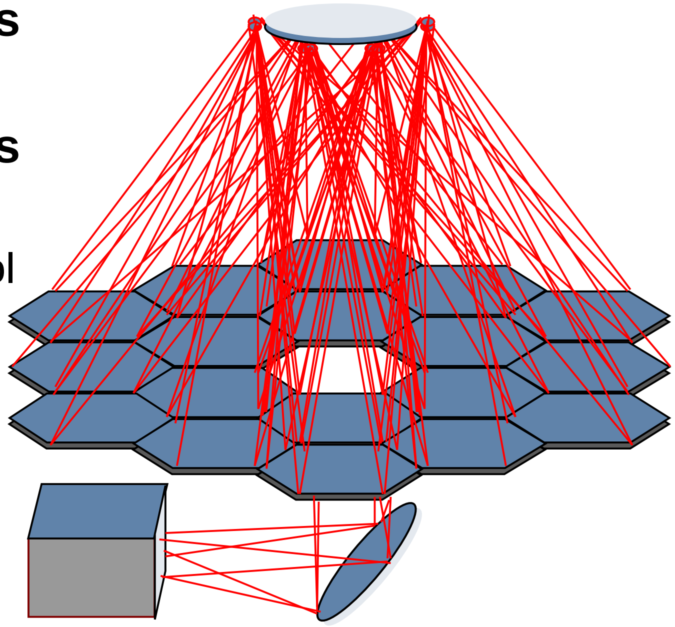
Parameter	Performance
Mode of operation	Relative only
Technology	Heterodyne
Heterodyne frequency	10-100 KHz
Laser wavelength	1500-1600 nm
Number of channels	8-110
Precision	<1 nm
Working distance	0-50 m
Data rate	100-2000 Hz
Max slew rate	+/-5 mm/sec
Laser power from beam launcher in free space	<5uW (eye safe)
Phase meter technique	Zero crossing
Laser- external cavity	20 mW

A Laser Distance Gauge



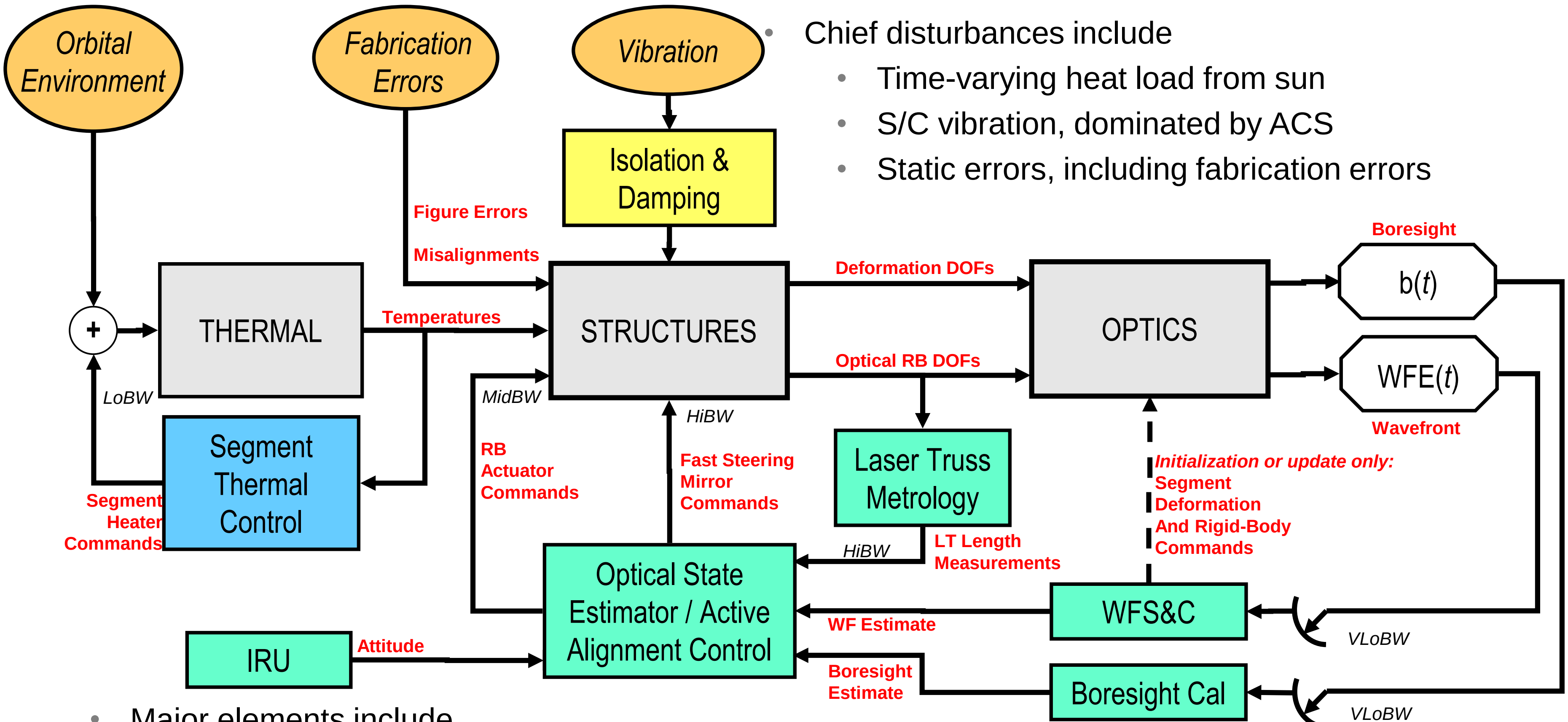
- A Laser Distance Gauge (LDG) is a “yardstick,” with “inchmarks” provided by the interference fringes of the laser beam
- Six LDGs between each segment and the SM, and from the SM to the back end, allows measurement of all OTA alignment errors, at high BW
- **Slow position feedback to Segment RB actuators 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

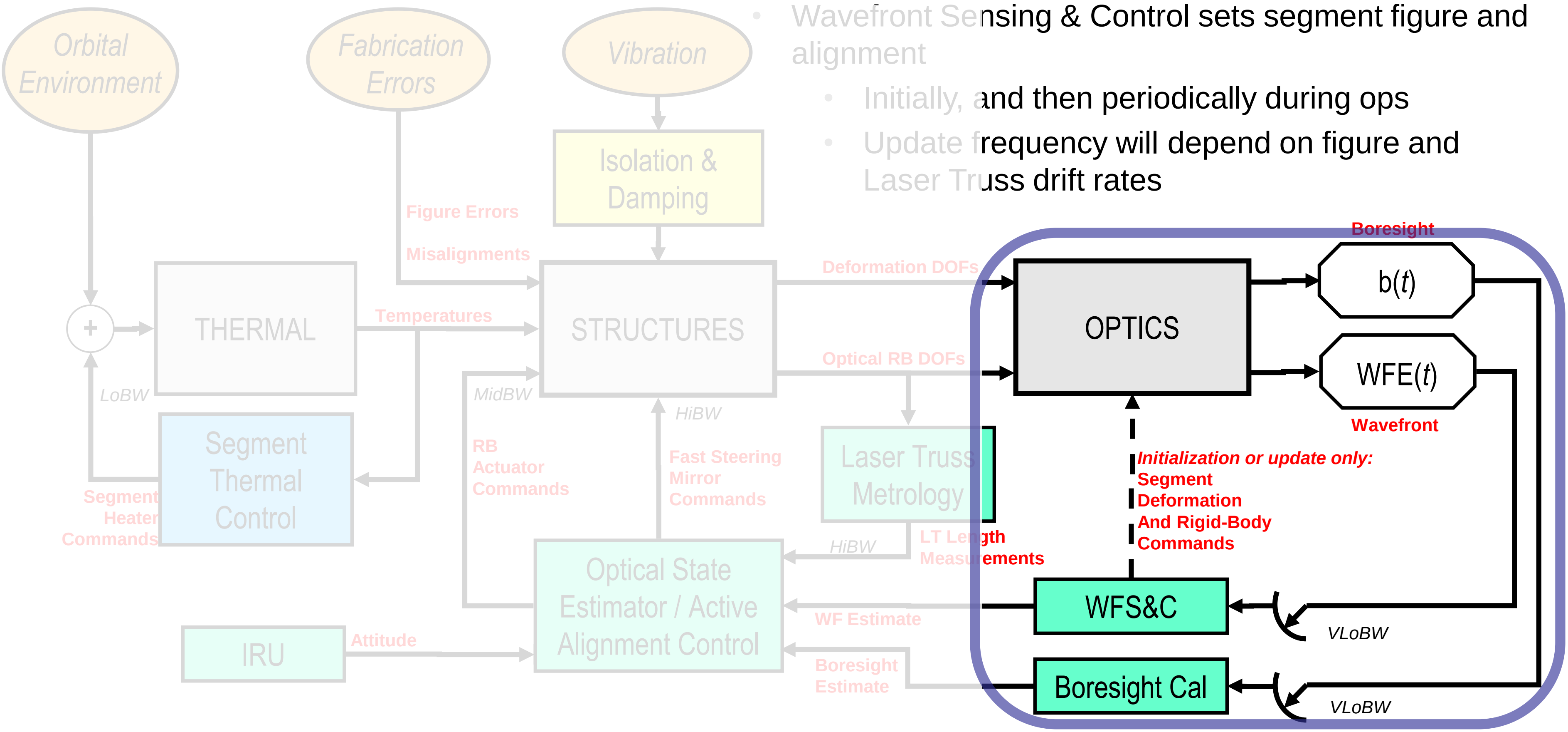
- Chief disturbances include
  - Time-varying heat load from sun
  - S/C vibration, dominated by ACS
  - Static errors, including fabrication errors



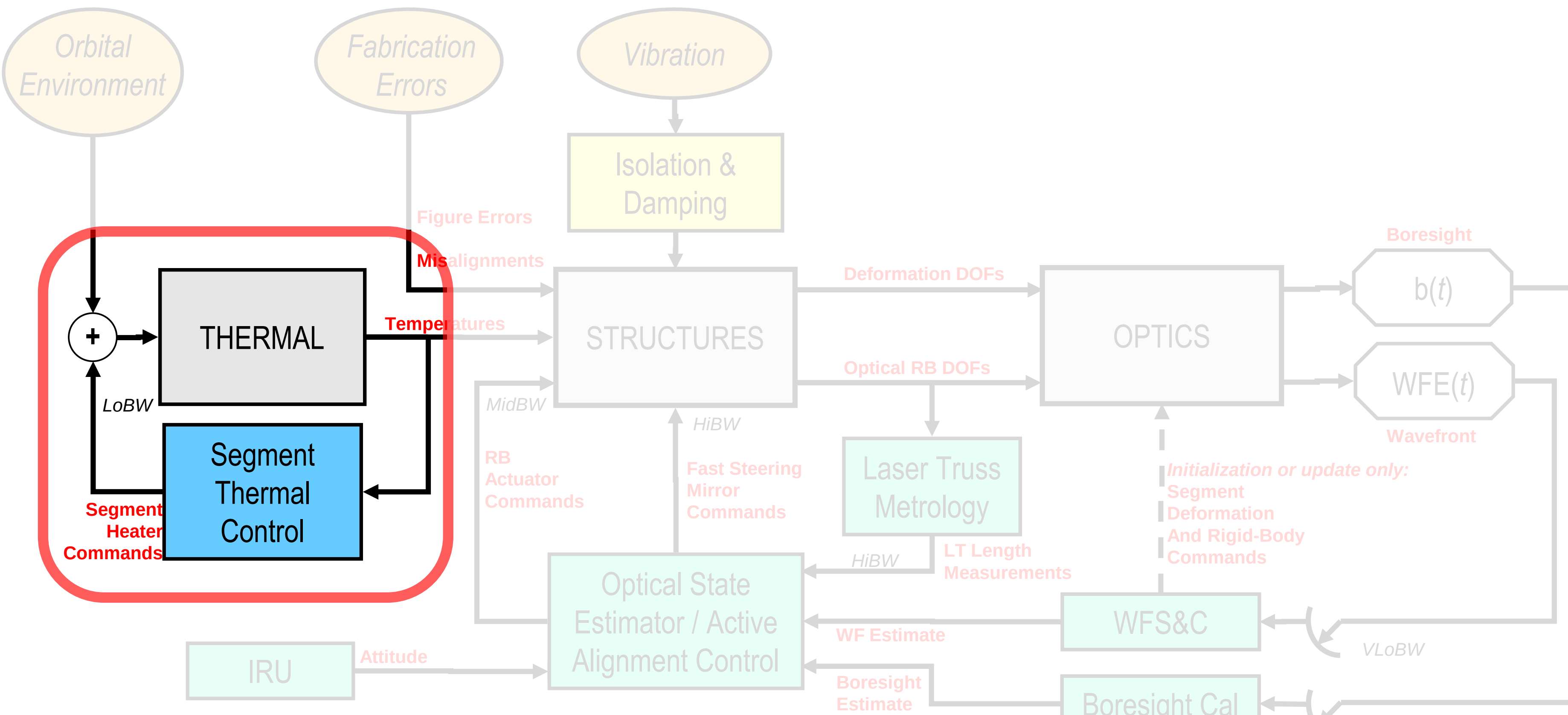
- Major elements include
  - Wavefront Sensing and Control
  - Laser Truss Active Alignment: active WF compensation and LOS pointing control
  - Segment Thermal Control to stabilize optical figure
  - Isolation and Damping to attenuate vibration disturbances

WFS&C

- Wavefront Sensing & Control sets segment figure and alignment
  - Initially, and then periodically during ops
  - Update frequency will depend on figure and Laser Truss drift rates



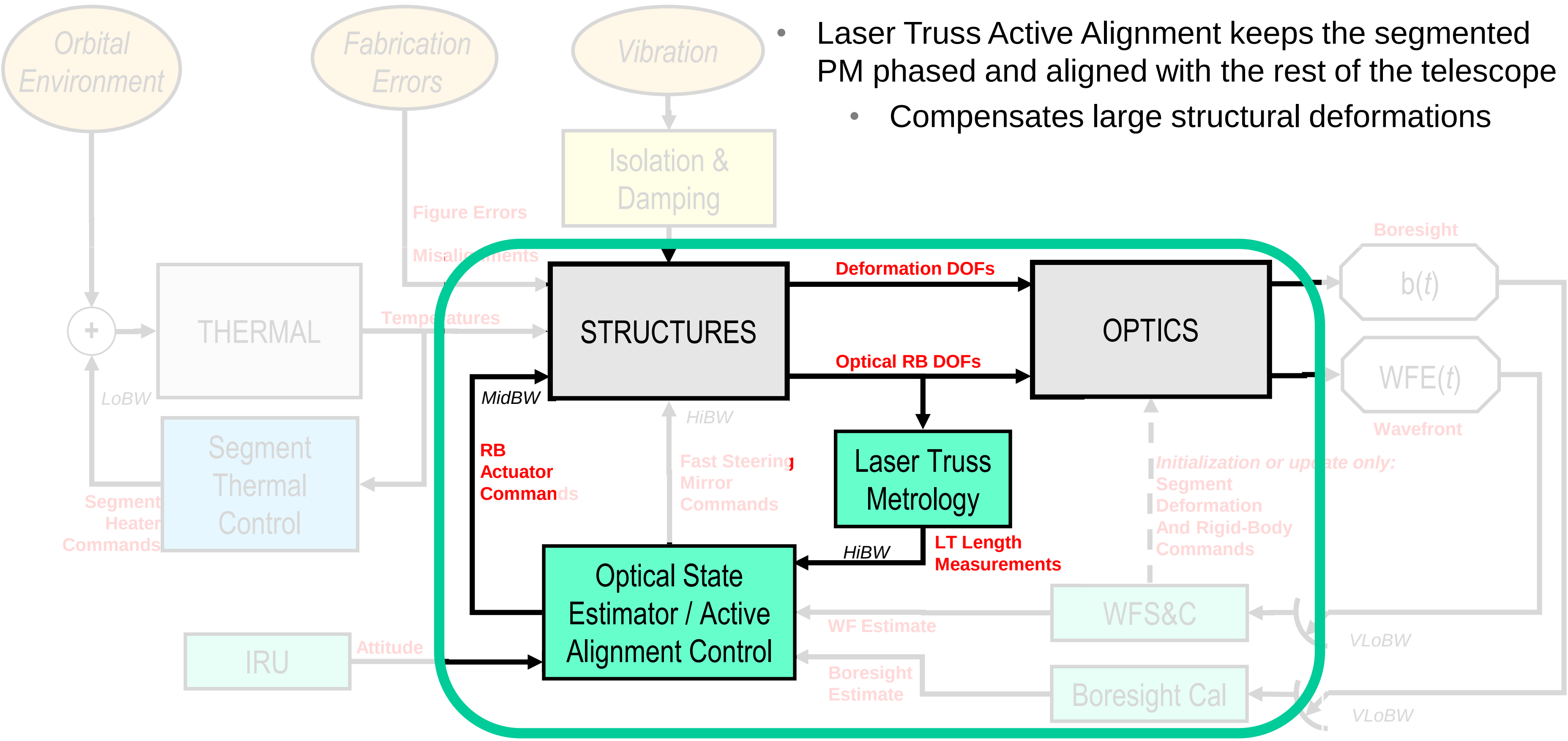
Thermal Control Preserves PM Figure



- Segment figure is thermally stabilized
  - Passive Athermalization: keeps WFE/°C very low
  - Passive Thermal Control: sunshade, operations constraints
  - Local Segment Thermal Control: PM segment temperatures are kept constant using heaters integrated with segment structure

Laser Truss Metrology Maintains Alignments

- Laser Truss Active Alignment keeps the segmented PM phased and aligned with the rest of the telescope
  - Compensates large structural deformations



- Laser Truss measurements at high BW are processed in the Optical State Estimator to estimate the perturbation state of all the optics
- Estimated state is fed back to control WFE using RBAs at low BW, and boresight at high BW using the Fast Steering Mirror

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