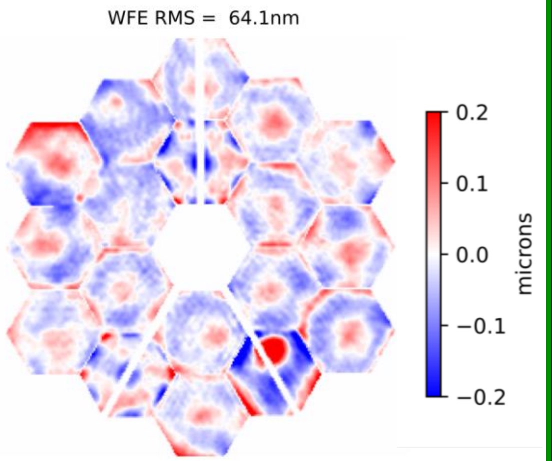
UV-Optical Telescope Technology

Lee Feinberg, NASA Goddard Space Flight Center

1/10/23

JWST Performance nearly 2x spec Gives High Confidence a .5um diffraction limited telescope is feasible

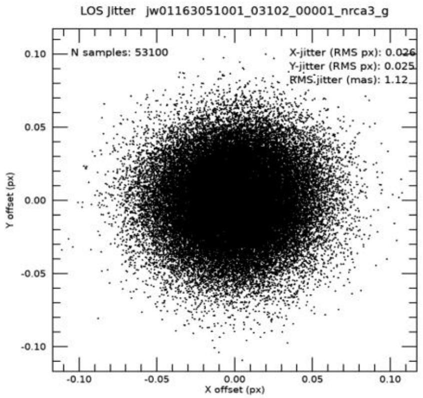
Telescope ~ 65 nm rms
Telescope + SIs ~ 70-130 nm



As of July 12th

λ/14 at 1.1 µm
λ/25 at 2.0 µm
λ/100 at 10 µm…

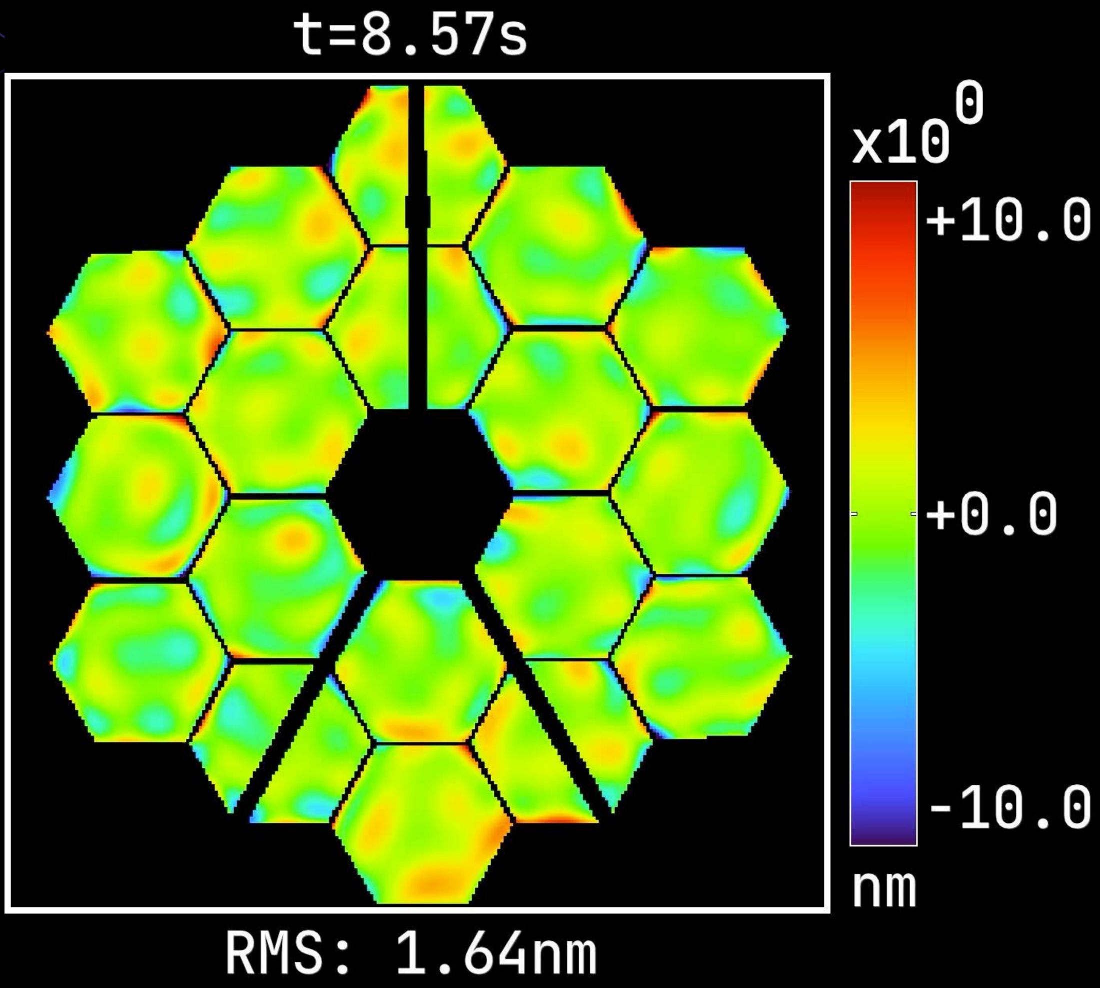
Absolute pointing < 0.2”
Line of sight jitter ~ 1 mas
Dither precision ~2-4 mas



No measurable vibration from cryocooler or reaction wheels

- Telescope performance is dominated by the primary mirror
  - WFE improvements needed for static WFE well within the state of the art (eg, <10nm RMS PMSA)
  - HWO is expected to be diffraction limited at .5um or about 37.5nm RMS WFE
- JWST’s 1 mas stability with simple isolation and 1hz fine steering loop
- Micrometeoroids can be reduced 100x with a baffle

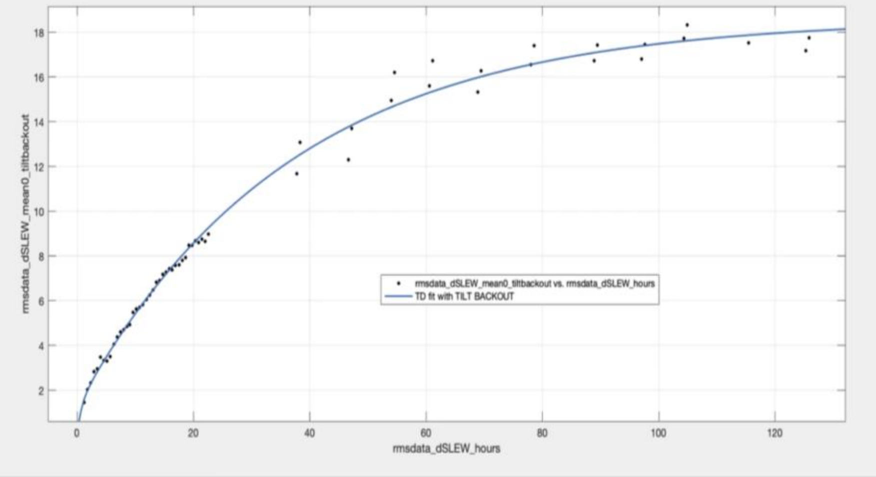
JWST passive thermal stability defines upper bounds for active controls



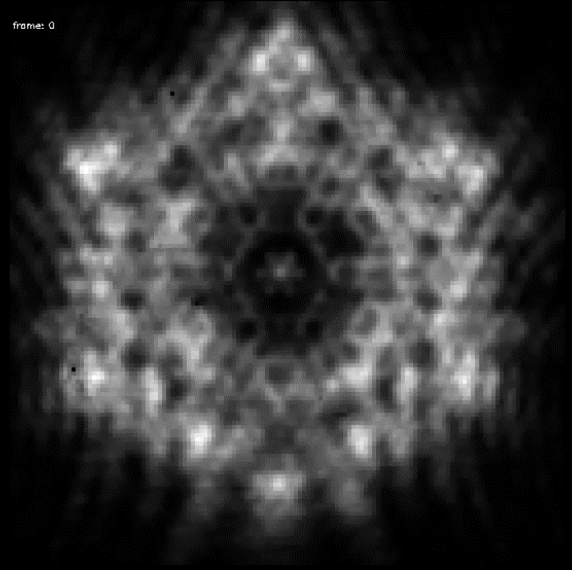
Short Term Oscillations result from heaters used on instrument electronics panels connected to PM with .5K deadband

- RST predicts 1mK class control on PM

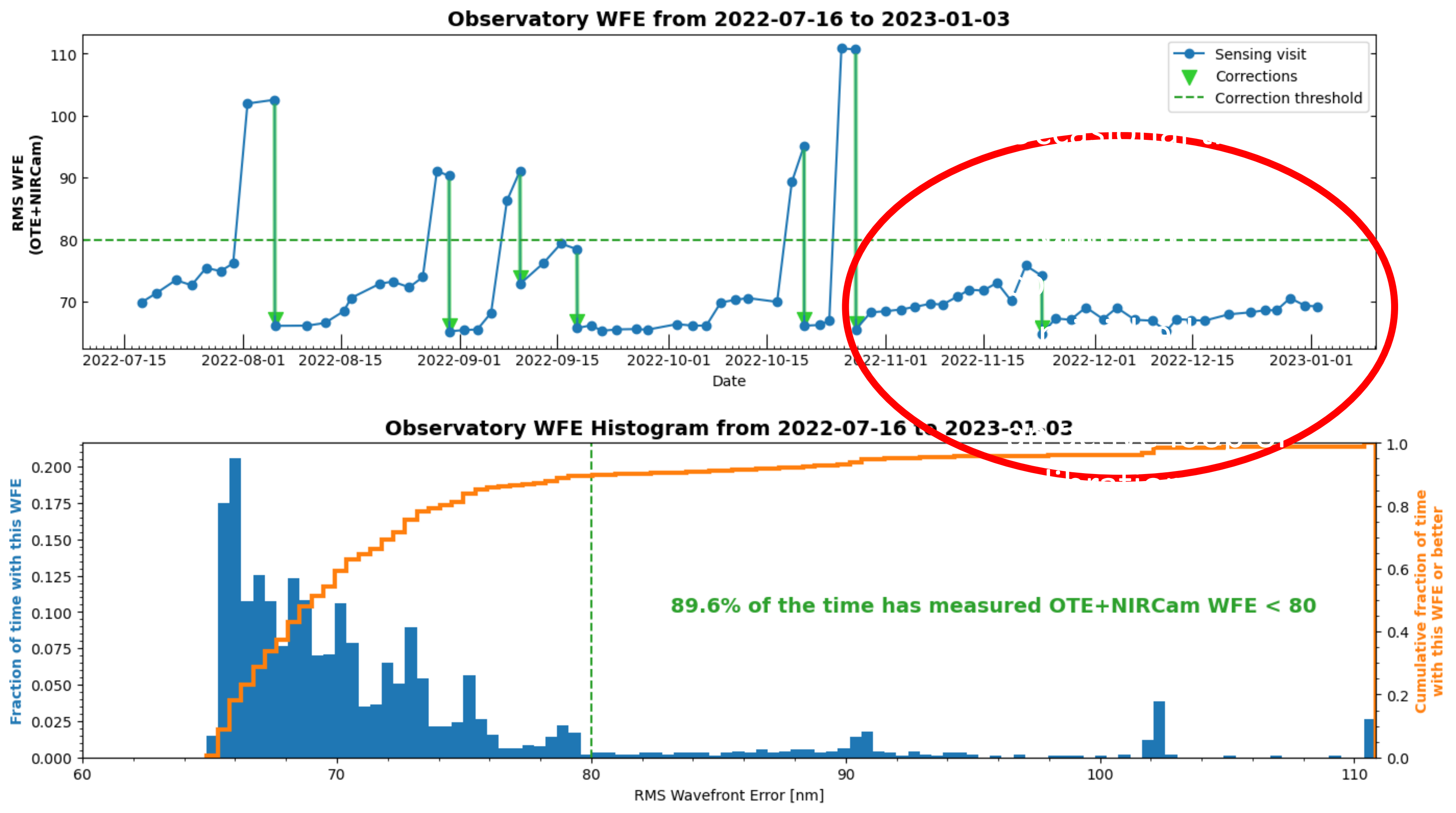
Alden Jurling, Joe Howard (NASA GSFC)



18 nm RMS WFE
over 8 days after nearly
worst case slew



No significant tilt events in nearly 2.5 months


Observatory WFE from 2022-07-16 to 2023-01-03

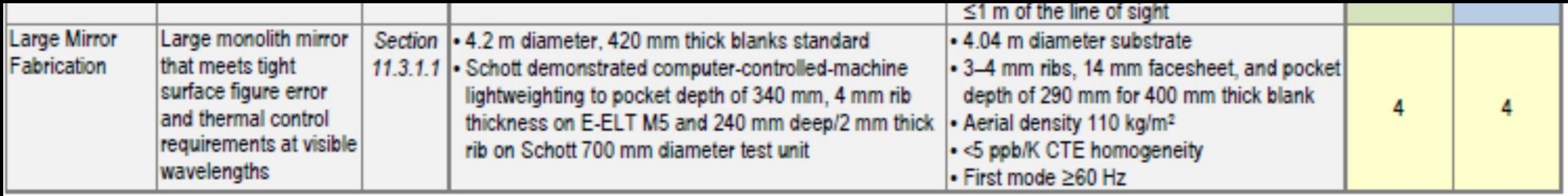
Observatory WFE Histogram from 2022-07-16 to 2023-01-03

89.6% of the time has measured OTE+NIRCam WFE < 80

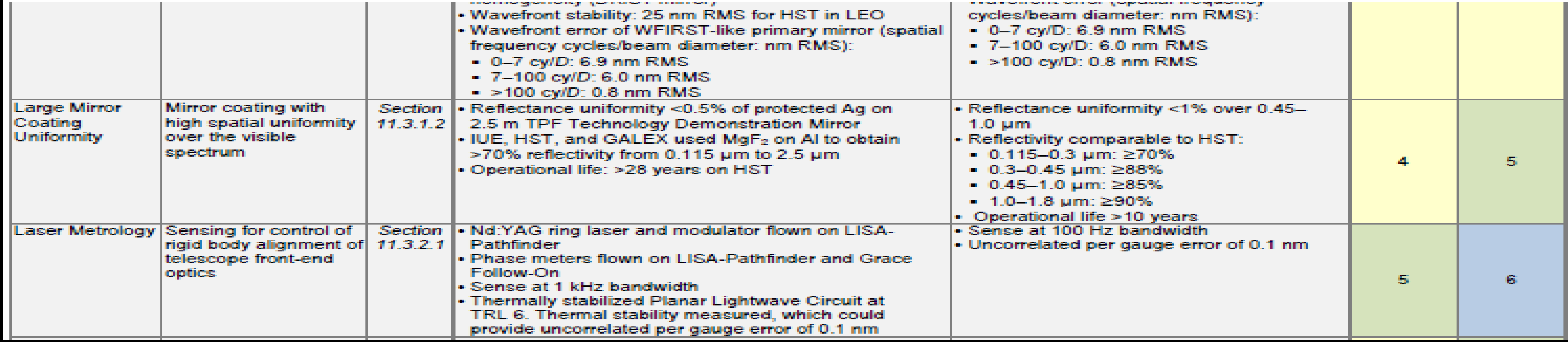
Significant tilt events are defined as large enough to warrant WFE correction

Occasional tilt events the first few months after cooldown have diminished, can be removed with an active loop or calibration

Habex Telescope Technologies (2019 assessment)



				≤1 m of the line of sight		
Large Mirror Fabrication	Large monolith mirror that meets tight surface figure error and thermal control requirements at visible wavelengths	*Section 11.3.1.1*	• 4.2 m diameter, 420 mm thick blanks standard • Schott demonstrated computer-controlled-machine lightweighting to pocket depth of 340 mm, 4 mm rib thickness on E-ELT M5 and 240 mm deep/2 mm thick rib on Schott 700 mm diameter test unit	• 4.04 m diameter substrate • 3–4 mm ribs, 14 mm facesheet, and pocket depth of 290 mm for 400 mm thick blank • Aerial density 110 kg/m² • <5 ppb/K CTE homogeneity • First mode ≥60 Hz	4	4



			• Wavefront stability: 25 nm RMS for HST in LEO
			• Wavefront error of WFIRST-like primary mirror (spatial frequency cycles/beam diameter: nm RMS):
			  ▪ 0–7 cy/*D*: 6.9 nm RMS
			  ▪ 7–100 cy/*D*: 6.0 nm RMS
			  ▪ >100 cy/*D*: 0.8 nm RMS
				cycles/beam diameter: nm RMS):
				  ▪ 0–7 cy/D: 6.9 nm RMS
				  ▪ 7–100 cy/D: 6.0 nm RMS
				  ▪ >100 cy/D: 0.8 nm RMS		

Large Mirror Coating Uniformity	Mirror coating with high spatial uniformity over the visible spectrum	*Section 11.3.1.2*	• Reflectance uniformity <0.5% of protected Ag on 2.5 m TPF Technology Demonstration Mirror
			• IUE, HST, and GALEX used MgF_2 on Al to obtain >70% reflectivity from 0.115 µm to 2.5 µm
			• Operational life: >28 years on HST
				• Reflectance uniformity <1% over 0.45–1.0 µm
				• Reflectivity comparable to HST:
				  ▪ 0.115–0.3 µm: ≥70%
				  ▪ 0.3–0.45 µm: ≥88%
				  ▪ 0.45–1.0 µm: ≥85%
				  ▪ 1.0–1.8 µm: ≥90%
				• Operational life >10 years
					4	5

Laser Metrology	Sensing for control of rigid body alignment of telescope front-end optics	*Section 11.3.2.1*	• Nd:YAG ring laser and modulator flown on LISA-Pathfinder • Phase meters flown on LISA-Pathfinder and Grace Follow-On • Sense at 1 kHz bandwidth • Thermally stabilized Planar Lightwave Circuit at TRL 6. Thermal stability measured, which could provide uncorrelated per gauge error of 0.1 nm	• Sense at 100 Hz bandwidth • Uncorrelated per gauge error of 0.1 nm	5	6

Assumed a 4m monolith

LUVOIR Telescope technologies (2019 assessment)

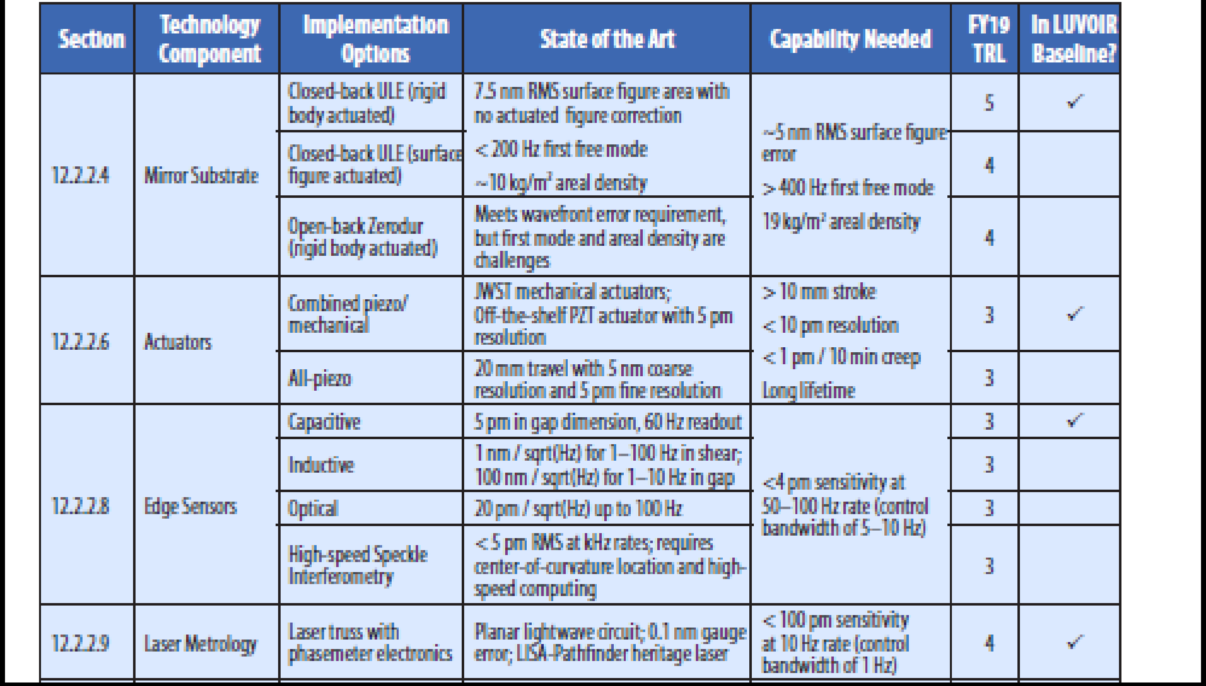


Table 11-2. *Technology components in the ultra-stable segmented telescope technology system.*

Section	Technology Component	Implementation Options	State of the Art	Capability Needed	FY19 TRL	In LUVOIR Baseline?
12.2.2.4	Mirror Substrate	Closed-back ULE (rigid body actuated)	7.5 nm RMS surface figure area with no actuated figure correction	~5 nm RMS surface figure error > 400 Hz first free mode 19 kg/m² areal density	5	✓
		Closed-back ULE (surface figure actuated)	< 200 Hz first free mode ~10 kg/m² areal density		4	
		Open-back Zerodur (rigid body actuated)	Meets wavefront error requirement, but first mode and areal density are challenges		4	
12.2.2.6	Actuators	Combined piezo/mechanical	JWST mechanical actuators; Off-the-shelf PZT actuator with 5 pm resolution	> 10 mm stroke < 10 pm resolution < 1 pm / 10 min creep Long lifetime	3	✓
		All-piezo	20 mm travel with 5 nm coarse resolution and 5 pm fine resolution		3	
12.2.2.8	Edge Sensors	Capacitive	5 pm in gap dimension, 60 Hz readout	<4 pm sensitivity at 50–100 Hz rate (control bandwidth of 5–10 Hz)	3	✓
		Inductive	1 nm / sqrt(Hz) for 1–100 Hz in shear; 100 nm / sqrt(Hz) for 1–10 Hz in gap		3	
		Optical	20 pm / sqrt(Hz) up to 100 Hz		3	
		High-speed Speckle Interferometry	< 5 pm RMS at kHz rates; requires center-of-curvature location and high-speed computing		3	
12.2.2.9	Laser Metrology	Laser truss with phasemeter electronics	Planar lightwave circuit; 0.1 nm gauge error; LISA-Pathfinder heritage laser	< 100 pm sensitivity at 10 Hz rate (control bandwidth of 1 Hz)	4	✓

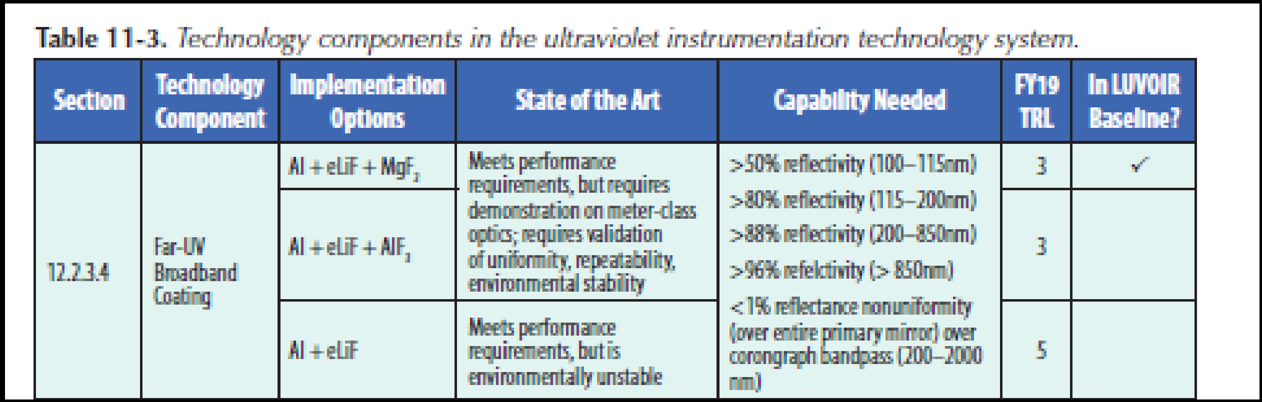


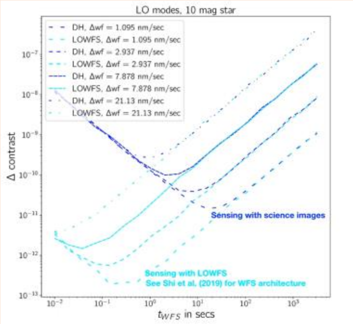
Table 11-3. *Technology components in the ultraviolet instrumentation technology system.*

Section	Technology Component	Implementation Options	State of the Art	Capability Needed	FY19 TRL	In LUVOIR Baseline?
12.2.3.4	Far-UV Broadband Coating	Al + eLiF + MgF_2	Meets performance requirements, but requires demonstration on meter-class optics; requires validation of uniformity, repeatability, environmental stability	>50% reflectivity (100–115nm) >80% reflectivity (115–200nm) >88% reflectivity (200–850nm) >96% refelctivity (> 850nm) < 1% reflectance nonuniformity (over entire primary mirror) over corongraph bandpass (200–2000 nm)	3	✓
		Al + eLiF + AlF_3			3	
		Al + eLiF	Meets performance requirements, but is environmentally unstable		5	

ULTRA-TM (Ball/NG/L3 Harris) Recent Progress

CORONAGRAPH SENSITIVITES

Calculate contrast stability vs. spatial-temporal domain, active WFSC in coronagraph, noise



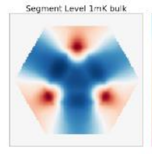

Relative Contribution of each mode.

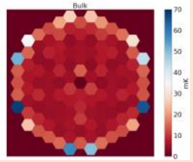
MID modes requirements with MIDWFS

Mag 0 star, < 15 pm/sec, $t_{WFS} > 0.5$ sec.

Mag 5 star, < 2 pm/sec, $t_{WFS} > 20$ sec.

Mag 10 star, < 0.5 pm/sec, $t_{WFS} > 2000$ sec.

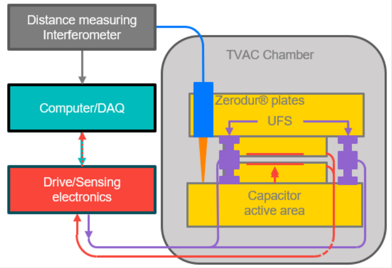


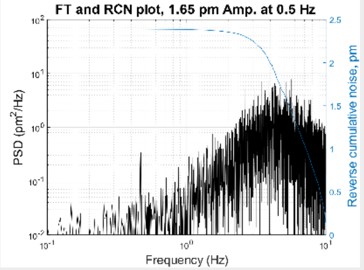


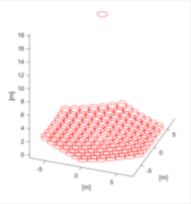
<u>Key Result</u>: Derived allocations for system stability budget, set necessary performance for systems/ subsystems/components, used to evaluate technology gaps

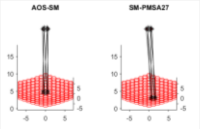
SEGMENT SENSING AND CONTROL

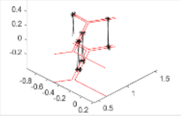
Demonstrate picometer-level edge sensor and actuator components with flight-traceable designs. Model network performance.

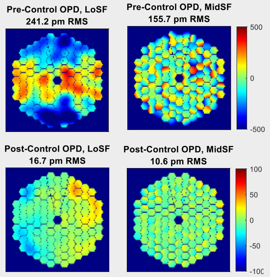








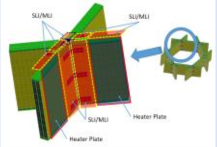


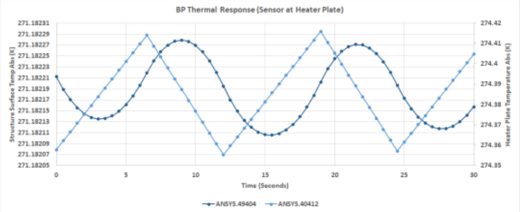


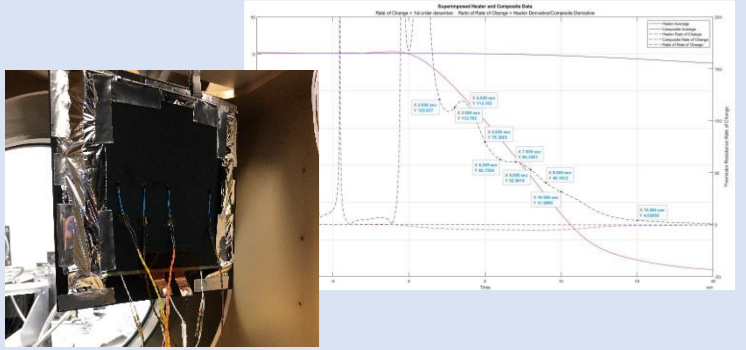
<u>Key Result</u>: Achieved 2.5 pm RMS closed loop sense/actuate residual from 0.01-10 Hz. Developed flexible time domain simulation for architecture trades and component evaluation

THERMAL SENSING AND CONTROL

Develop a radiative heating approach with stability in the mK regime





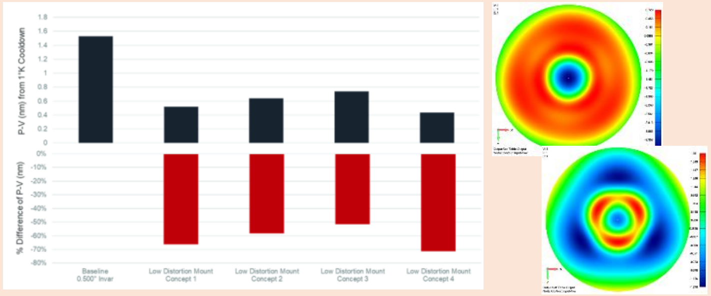


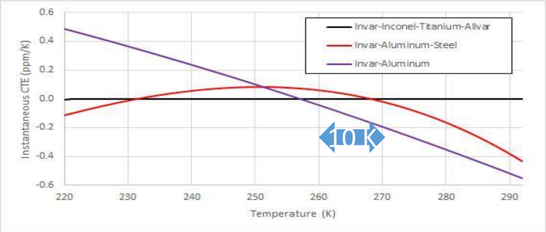
<u>Key Result</u>: Modeling and hardware demo of sub-mK thermal stability from rigid heater-integral-to-composite heater panel on structure element. Identified novel temp sensors.

ULTRA-TM Progress (Continued)

STABLE MIRROR MOUNTING

Design of novel mount pads, struts with improved passive stability to reduce mirror distortion

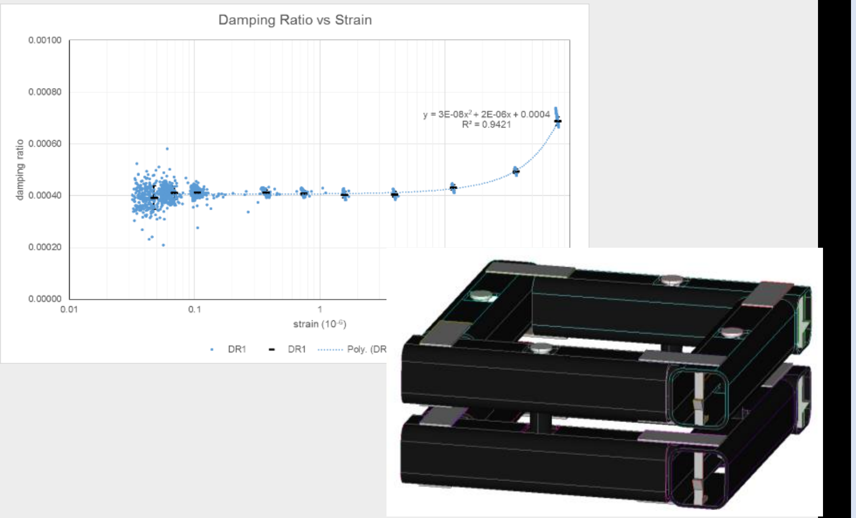




<u>Key Result</u>: Design and hardware demo of novel pad geometry with predicted 15-20X reduction in SFE distortion over solid pad.
Developed strut design with metal alloys that has comparable CTE to ULE/Zerodur.

STABLE STRUTURES – LATCHING AND DAMPING

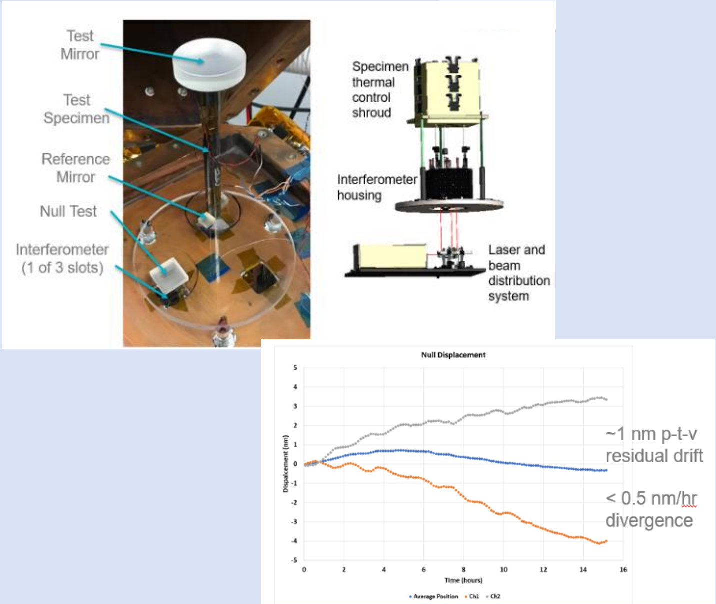
Increase damping in large structures with foil treatment. Re-design latches to improve passive thermal & dynamic stability.



<u>Key Result</u>: Hardware demo showed foil appreciably increased damping ratio in composite coupons. Hardware demo of latchplane test article showed new design reduces deformation by several orders of magnitude.

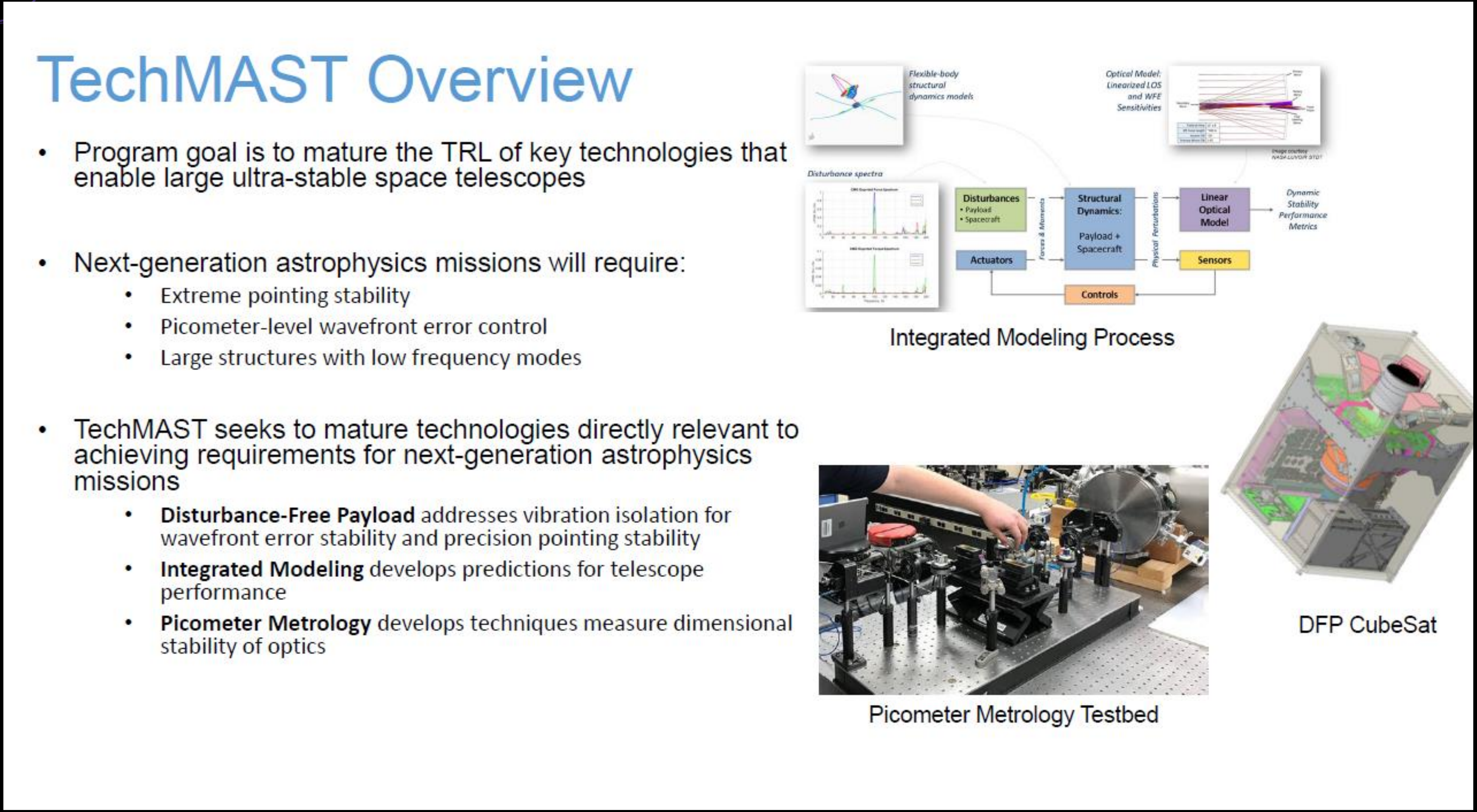
MATERIAL PROPERTY METROLOGY

Reduce uncertainty in measured CTE/CME of composites by 100X



<u>Key Result</u>: 10X improvement in displacement measurement. Improved isolation from lab environment. Completed analysis of alignment stability on displacement.

Lockheed Martin Developments



TechMAST Overview

- Program goal is to mature the TRL of key technologies that enable large ultra-stable space telescopes

- Next-generation astrophysics missions will require:
  - Extreme pointing stability
  - Picometer-level wavefront error control
  - Large structures with low frequency modes

- TechMAST seeks to mature technologies directly relevant to achieving requirements for next-generation astrophysics missions
  - **Disturbance-Free Payload** addresses vibration isolation for wavefront error stability and precision pointing stability
  - **Integrated Modeling** develops predictions for telescope performance
  - **Picometer Metrology** develops techniques measure dimensional stability of optics

Integrated Modeling Process

DFP CubeSat

Picometer Metrology Testbed

Predictive Thermal Control (PTC) Technology to Enable Thermally Stable Telescopes

PI: H. Philip Stahl / MSFC
Co-I Thomas Brooks / MSFC

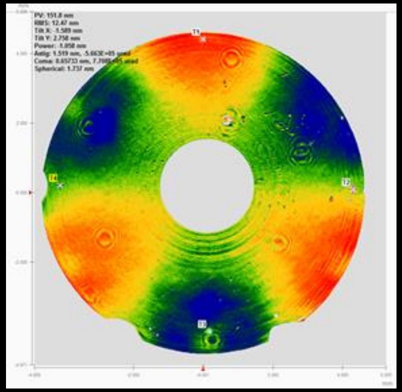
Objectives and Key Challenges:

- Validate models that predict thermal optical performance of real mirrors and structure based on their structural designs and constituent material properties, i.e. CTE distribution, thermal conductivity, thermal mass, etc.
- Derive thermal system stability specifications from science-driven wavefront-stability requirement
- Demonstrate utility of PTC system for achieving thermal stability

Significance of Work:

- Thermally stable space telescopes enable the desired science of potential HabEx and LUVOIR missions
- Integrated modeling tools enable better definition of system and component engineering specifications

PTC control system achieved 2K accuracy with 2mK stability of 1.5-m AMTD-2 ULE® mirror



Thermal zones able to impose 150 nm of trefoil

Approach:

- Science-driven systems engineering
- Mature technologies required to enable highest-priority science resulting in high-performance, low-cost, low-risk system
- Mature technology in support of 2020 Decadal process

Key Collaborators:

- Thomas Brooks, Richard Siler, and Ron Eng (NASA/MSFC)
- Carl Rosoti, Keith Harvey, and Rob Egerman (Harris Corp)

Funded Period of Performance:

Jan 2017 – Sep 2021
(awarded as competed SAT, converted to ISFM directed work)

Accomplishments:

- ✓ Successfully completed all initial PTC objectives and milestones
- ✓ Demonstrated PTC multi-zone thermal control via test of a 1.5-m ULE® mirror in a relevant thermal/vacuum environment.
- ✓ Demonstrated figure correction via multi-zone thermal control
- ✓ Published study results in JATIS journal paper

Applications:

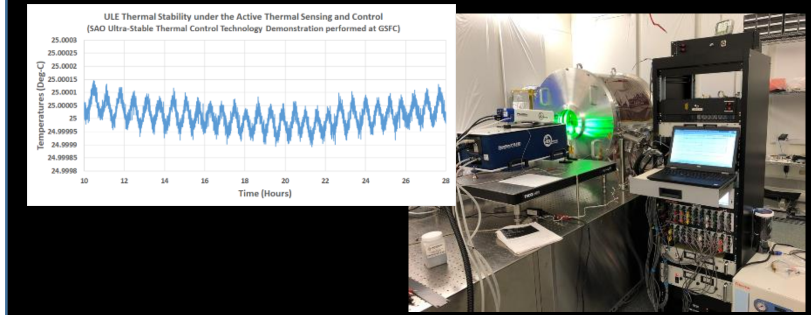
- Flagship and Explorer-class optical missions
- Department of Defense and commercial observations

TRL $_{In}$ ***= 3 TRL*** $_{Current}$ ***= 5+ TRL*** $_{Target}$ ***= 4 - 5***
(values depend on specific technology)

Other Relevant Telescope Technology

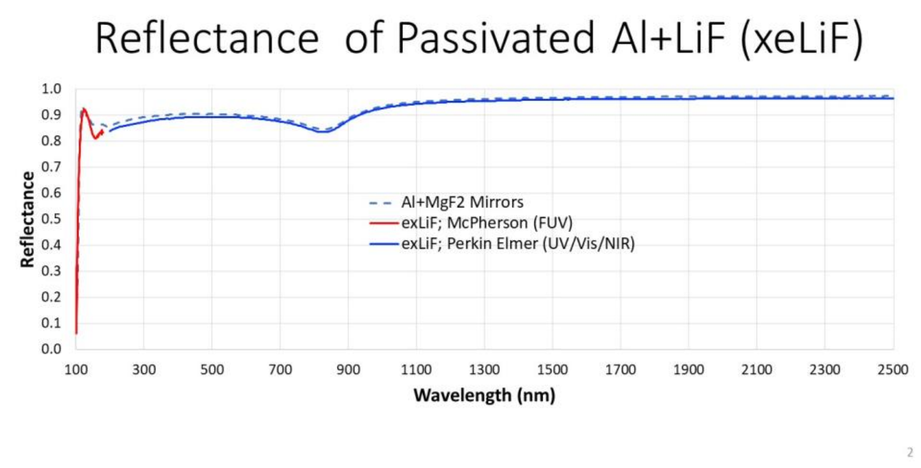
Ultrastable Telescopes

- +-75uK thermal control, pm/s drift measurements

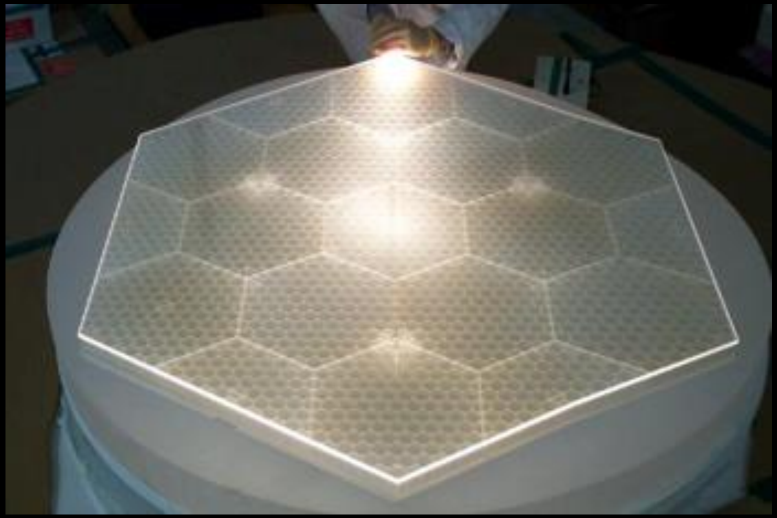


Thermal stability was demonstrated to less than **0.15mK P-V (150uK or +/- 75 µK) over an hour** with pm/s drifts measured interferometrically. <10pm noise in drift measurements

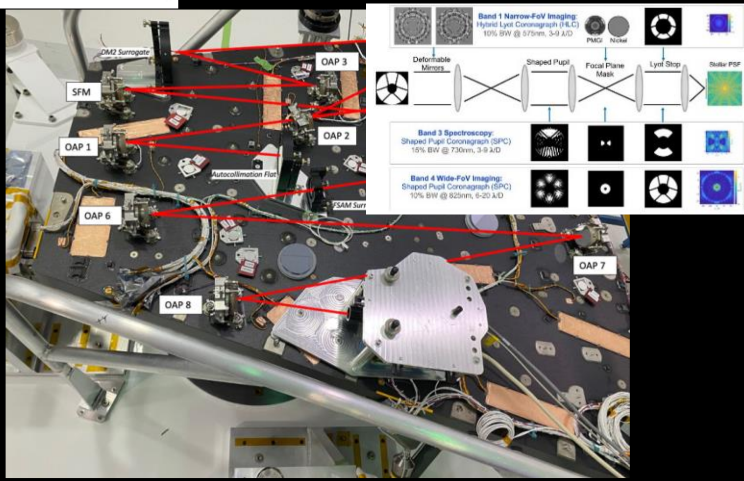
GSFC Ultrastable testbed/Picometer High Speed Interferometry



Coatings
M. Quijada/GSFC



Lightweight ULE Mirrors



Roman Space Telescope Coronagraph/JPL

Next Steps

- Update Telescope Technology Roadmaps Consistent both With Progress and The Decadal Recommendation and Develop Initial Investment Strategy
  - Need updated investment strategy for next fiscal year (gaps after SAT’s)
    - Prioritize enabling technologies, tall polls
    - Consider facilities and facility needs in the future
- Science/Architecture/Technology Studies:
  - Focus first on key driving architectural decisions
  - Error budgets/sensitivities/calibration developed to flow requirements
- Critical that science, technology development and system/architecture studies happen in parallel and iterate