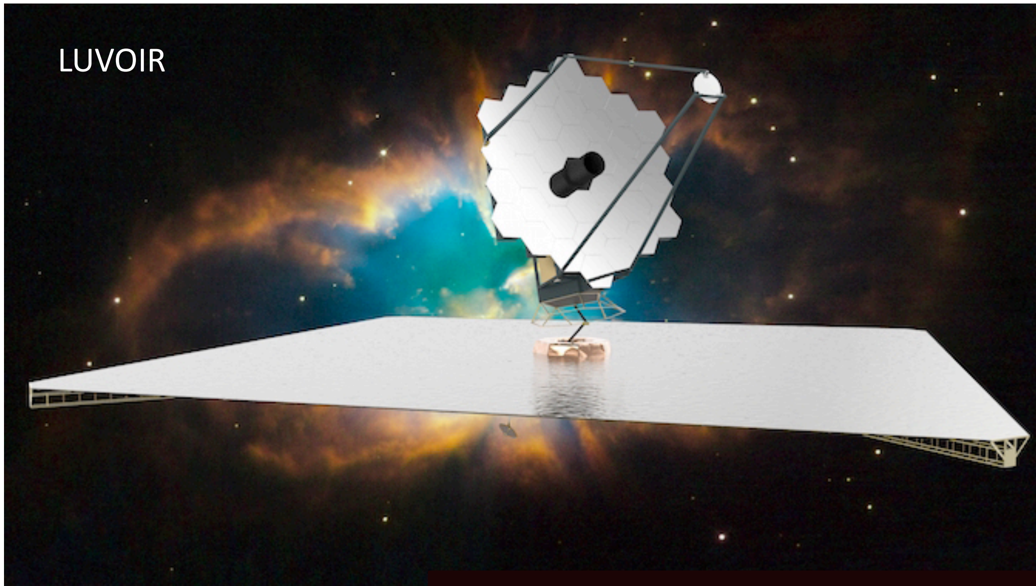
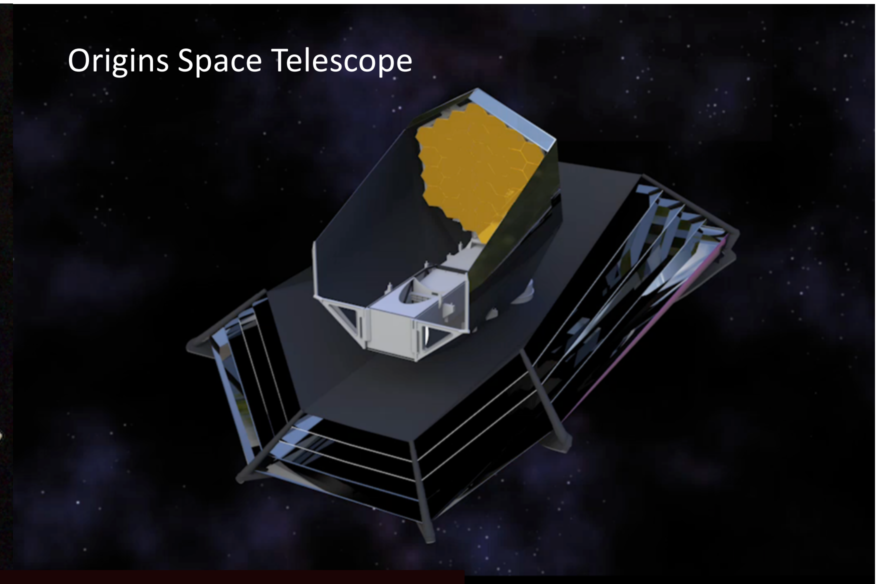
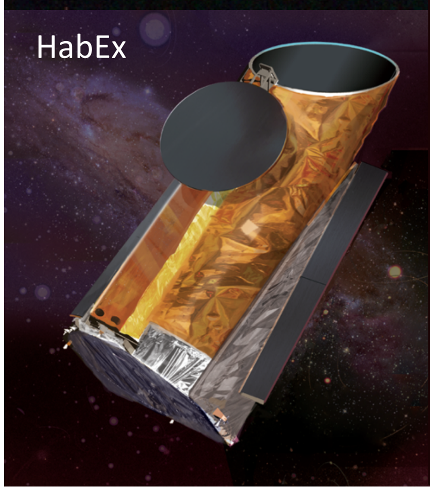
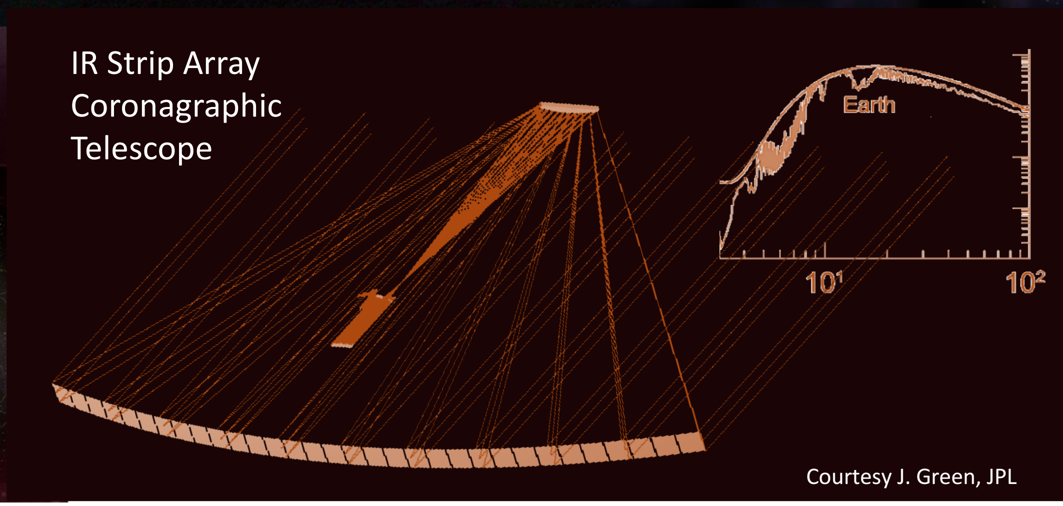
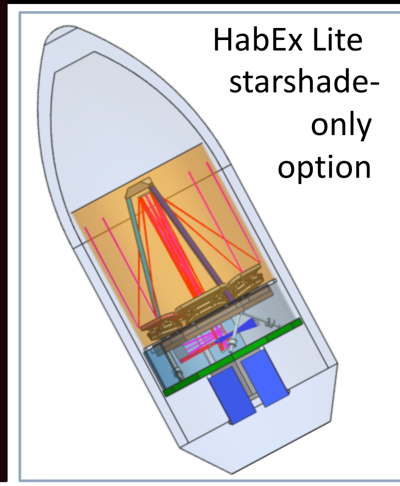










Workshop on Technology for Direct Detection and Characterization of Exoplanets

Large Segmented Apertures in Space

Active vs. Passive

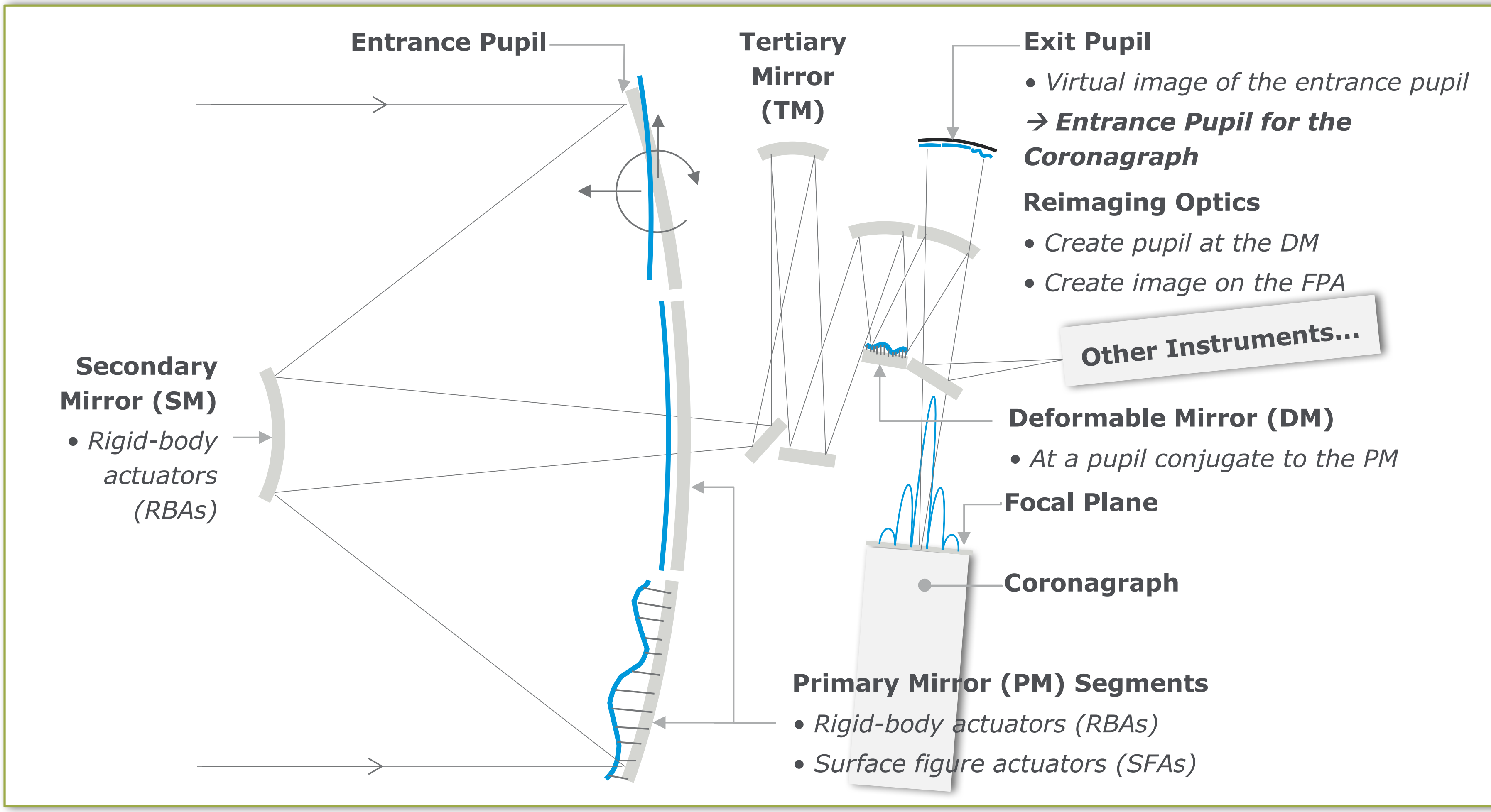
David Redding

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

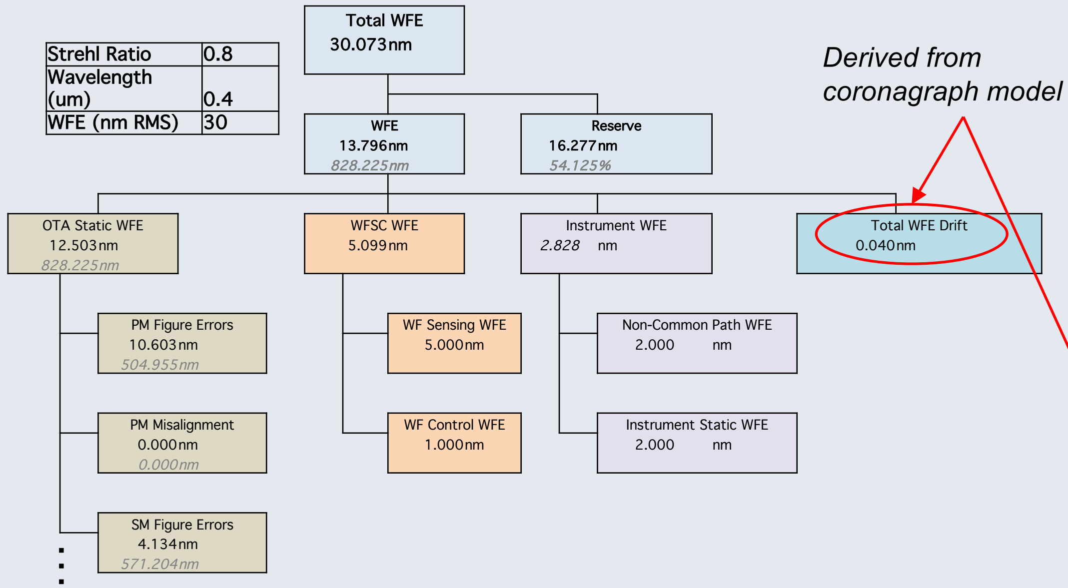
Jet Propulsion Laboratory
California Institute of Technology

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

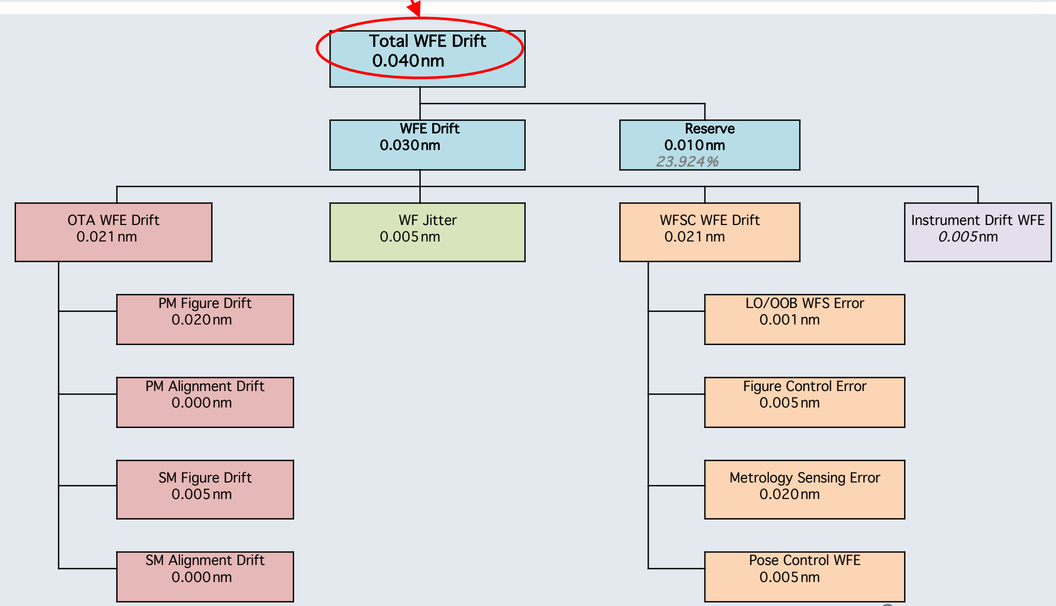


Notional Error Budgets: UVOIR



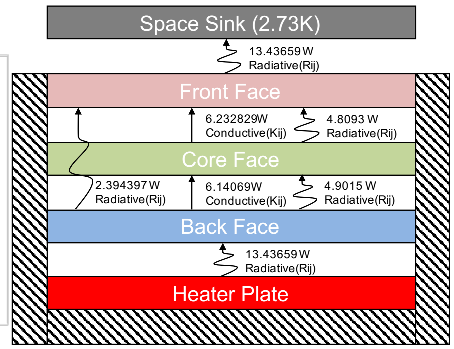
- Total Static WFE for a HabEx or LUVOIR is ~30 nm RMS
  - After initial WFSC
  - During all observations
  - With maintenance controls

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

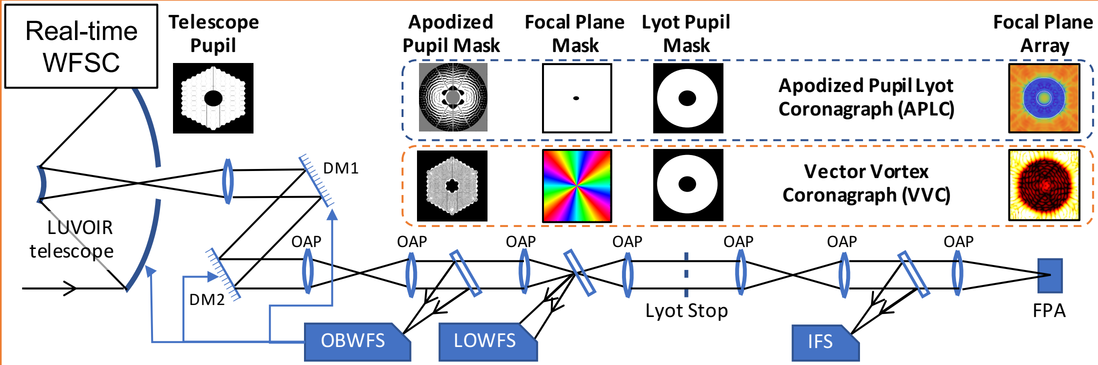


Active Control Methods for Ultra-Stability

Active Thermal Control

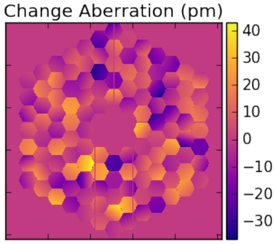


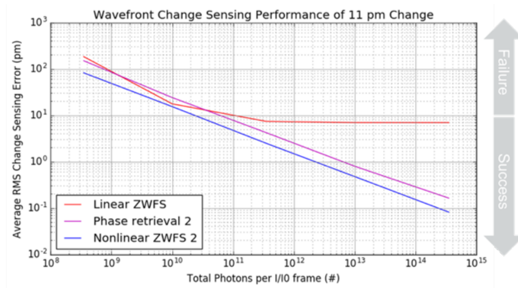
Real-time WFSC



Picometer WFS

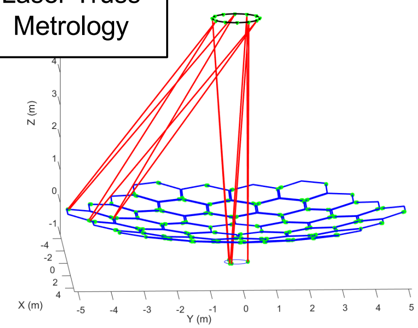
Change Aberration (pm)

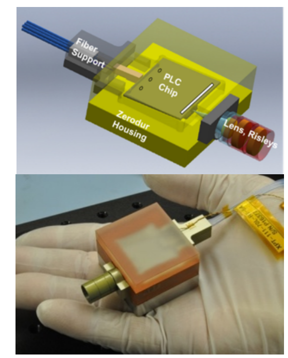




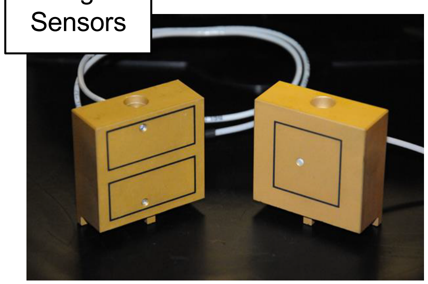
- 2×10^{10} photons available in 95 s exposure of 10^{th} magnitude star
  - Assuming B-band, 22% bandwidth, 135 m^2 aperture and *no losses*

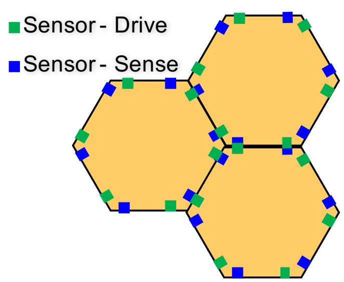
Laser Truss Metrology





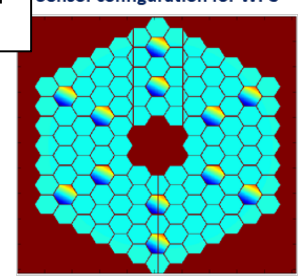
Edge Sensors





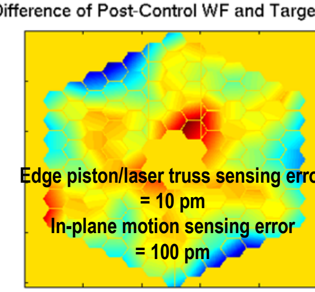
Combinations of techniques

Sensor configuration for WFC



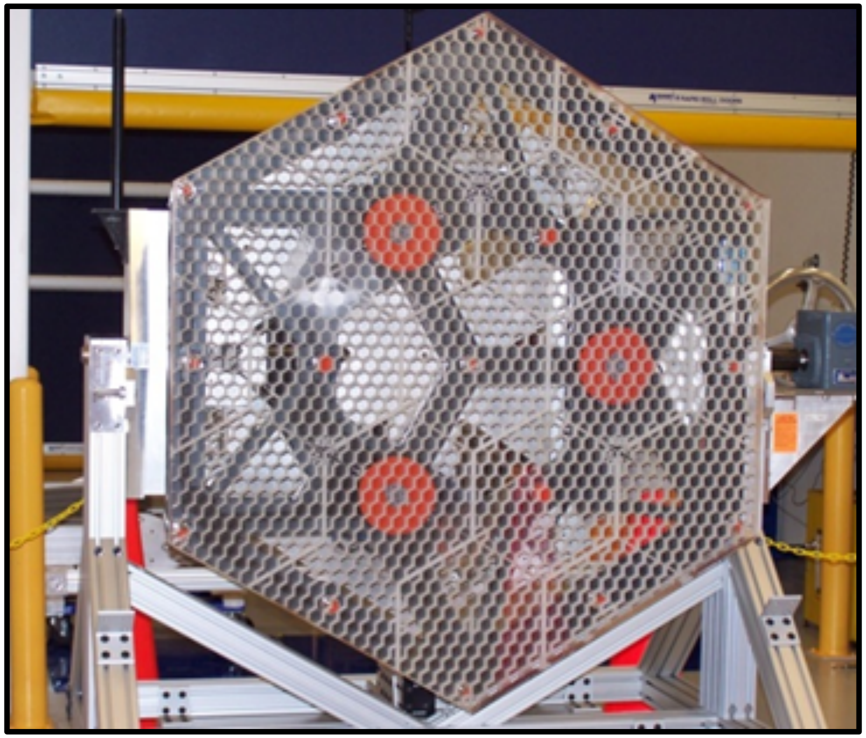
Edge sensing on all segments
Metrology on 12 segments, WEM = 2.99

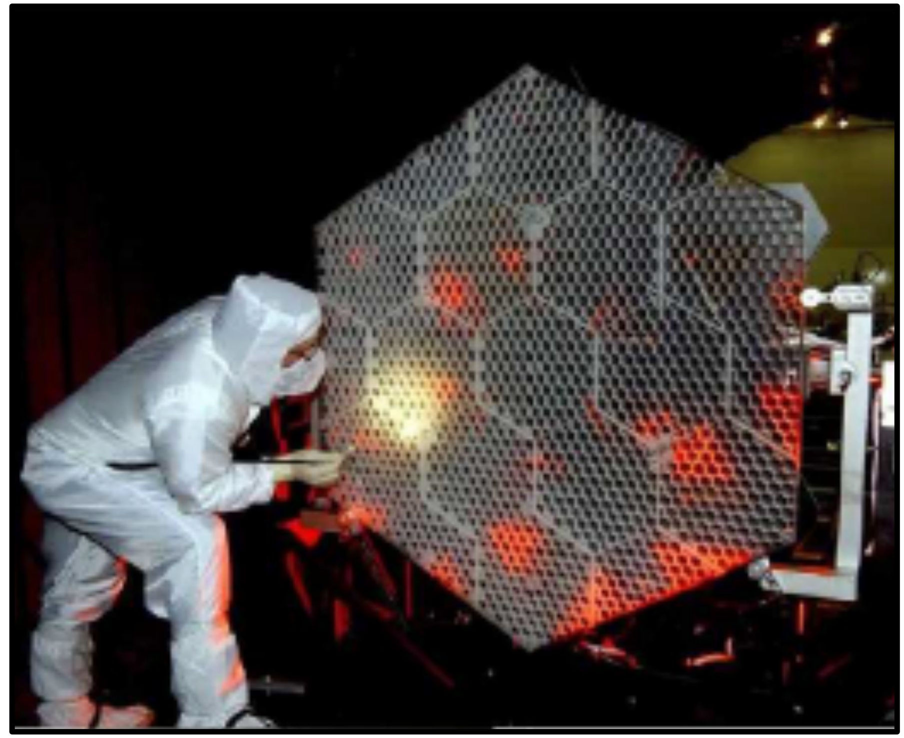
Difference of Post-Control WF and Target WF



RMS =0.042948 nm

ULE Mirrors: Passive and Low-Authority Active



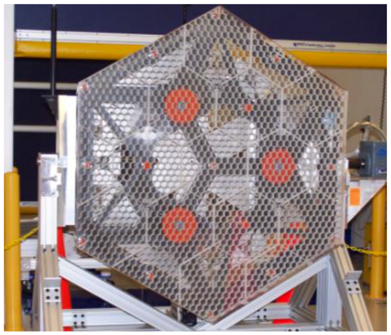


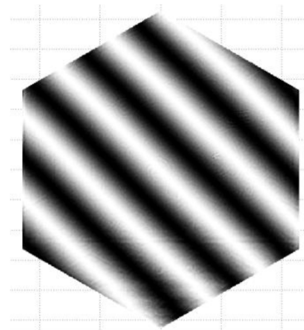
- ULE mirror segment technology. Harris (previously Kodak) has designed, fabricated and tested lightweight, passive and low-authority ULE segments. Harris has recently developed Capture Range Replication technology, enabling replication of mirrors to within capture range of final processes for figure 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.

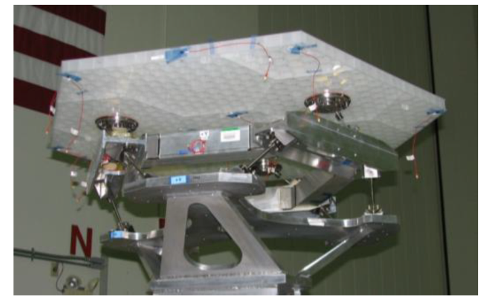
Demonstrations of ULE® Solution

HARRIS®

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







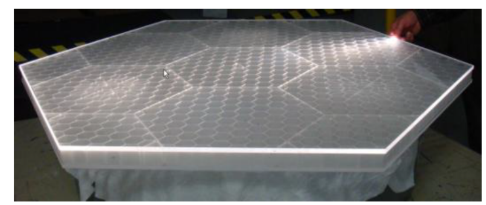
A. OTM PMSA (Optical Test Model)
- Mirror is existing 1.4m AMSD mirror refinished for MMSD
- New MMSD mounts, actuators, reaction structure, elec, controls
- 0-G figure and figure control demonstrated via optical test with both 10 and 16 FCA configurations

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/m^2 mirrors

Production rate on 3.5 week centers



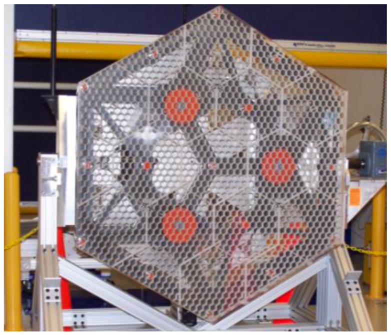
D. Mirror Segment D
- New full size MMSD mirror
- Completed thru plano fusion

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

Demonstrations of ULE® Solution

HARRIS®

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



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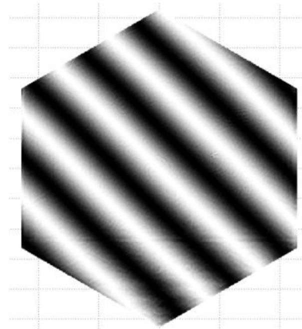
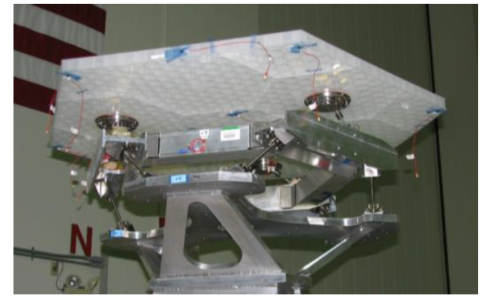


B. Mirror Segment B
- New full size MMSD mirror
- 0-G optical finishing demo
- Finished to 16 nm RMS WFE (no actuation)

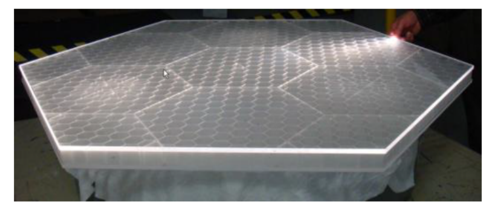


C. Mirror Segment C
- New full size MMSD mirror
- Finished thru LTS (100 um PV)
- Mounted & tested to high level random vibe & shock

Key validations achieved on each of these 10kg/m^2 mirrors

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

Production rate on 3.5 week centers

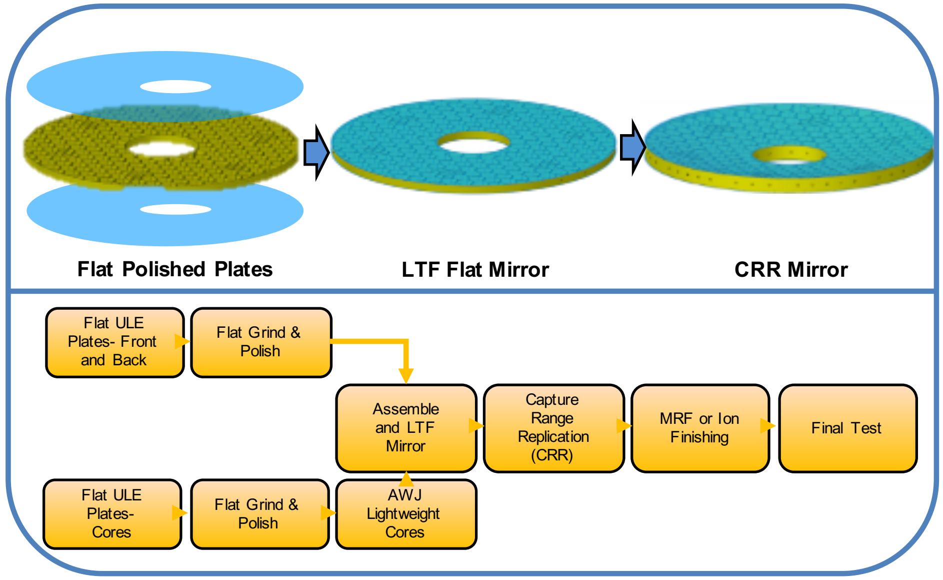


E. Mirror Segment E
- New full size MMSD mirror
- Completed thru plano fusion

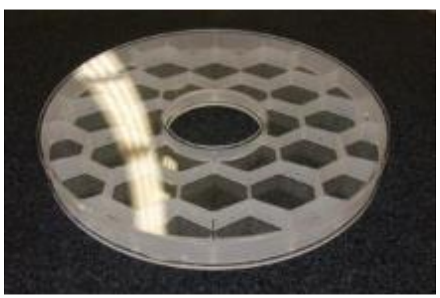
https://asd.gsfc.nasa.gov/conferences/uvvis/flagship/UVVis_Flagship_Matthews.pdf

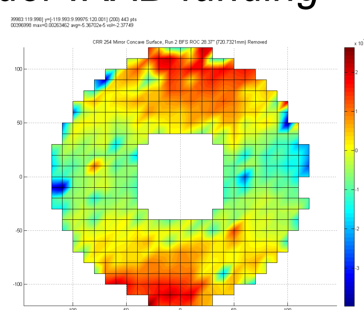
Harris Capture Range Replication

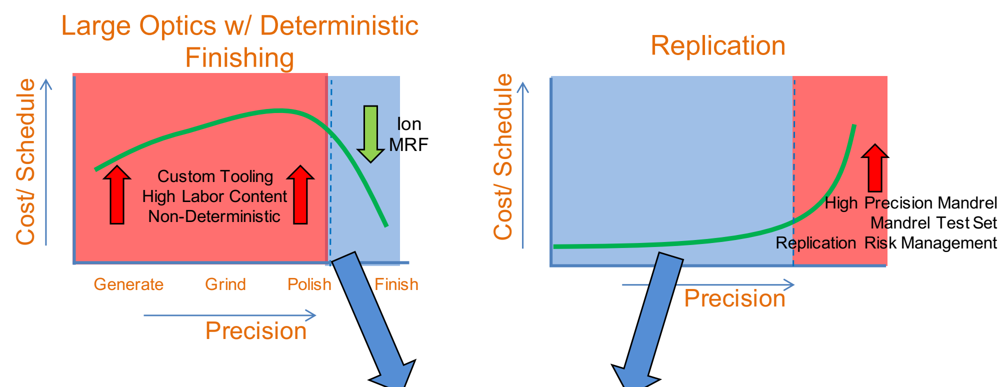
- Capture Range Replication uses precision mandrels and low-temperature slumping to replace traditional generate-grind-polish processes
- CRR finishes a mirror blank to within capture range for final finishing (MRF or Ion Beam)
- Result is a repeatable, efficient process for ULE mirror fabrication, saving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

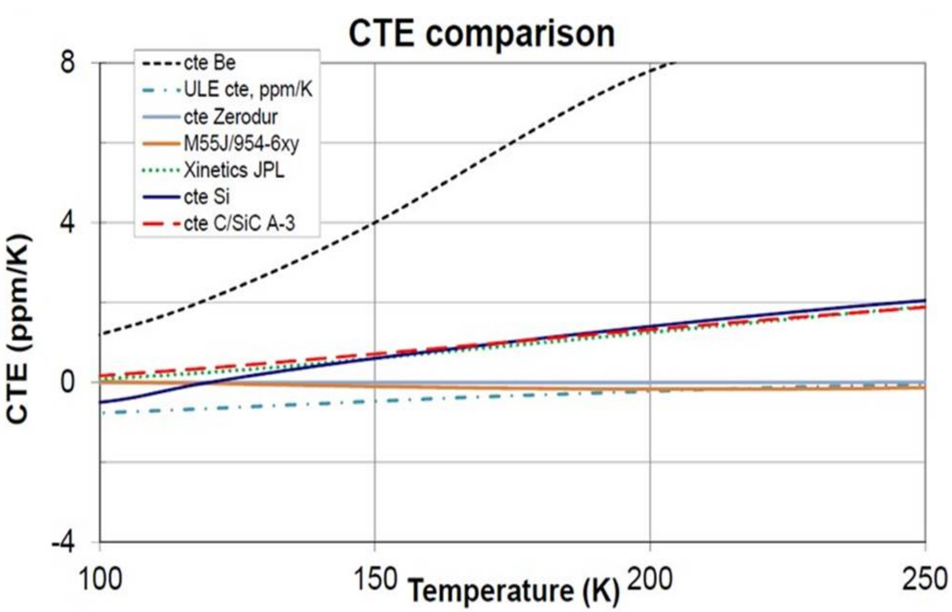
- AMSD and MMSD programs at Harris/Exelis/Kodak developed lightweight ULE mirror segments
- Further development has advanced manufacturability and lowered cost and schedule
- Low-authority architecture uses ~24 FCAs to compensate the most challenging fab errors
  - Meet 10 nm RMS figure error over full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

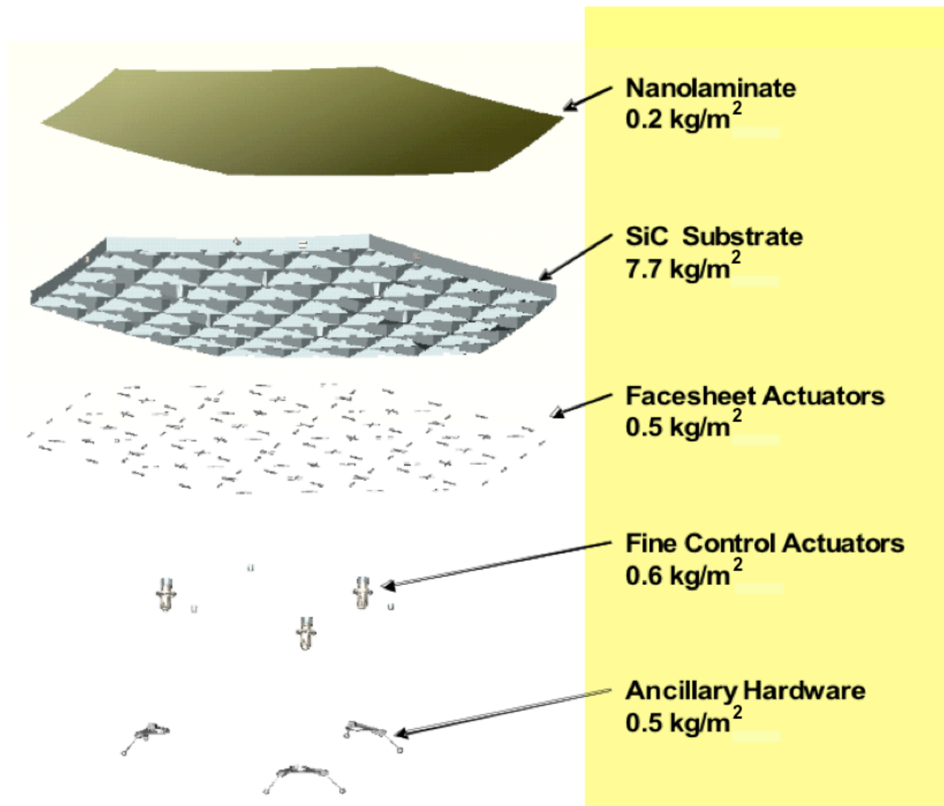
Property	Units	Aluminum	Beryllium	SiC	ULE	Desire
ρ, Weight	g/cm3	2.71	1.85	2.95	2.21	Low
E, Stiffness	GPa	68.3	303	364	67.6	High
E/ρ,Specific Stiffness	KN-m/g	25	164	123	31	High
σ/ρ, Stress Loading	N-m/g	46	11	24	3.2	High
α,Thermal Soaks	ppm/°C	22.7	11.4	3.38	±0.03	Low
Δα Homogeneity	ppb/°C	100	100	30	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)

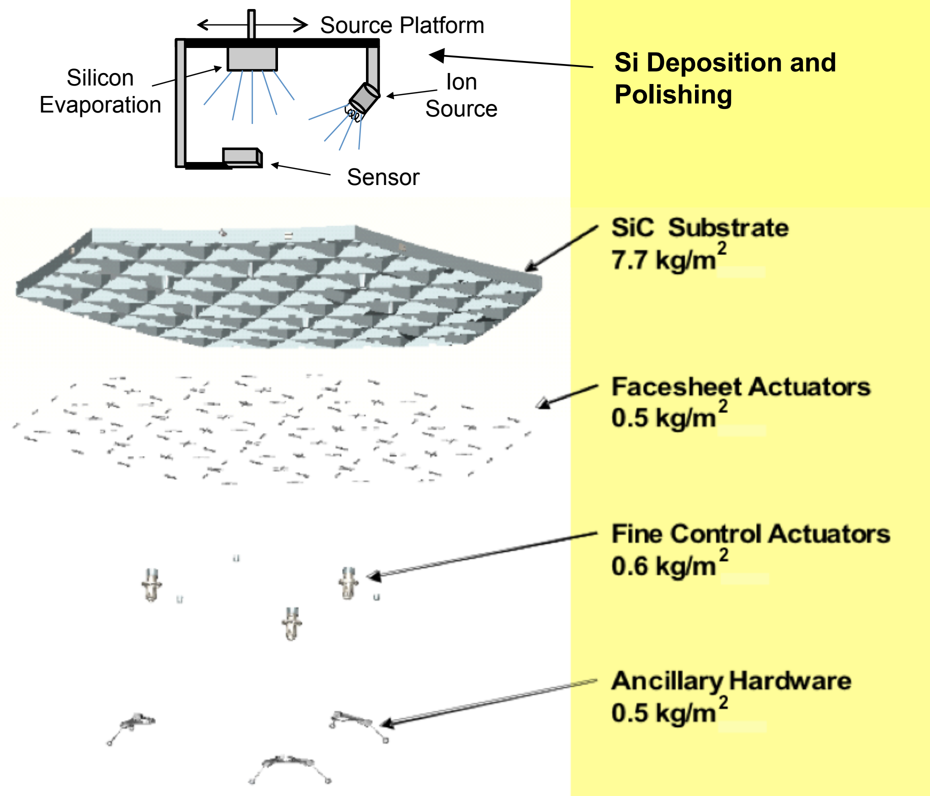
- AHMs are large mirrors
  - PMs or PM segments
  - Made by replication
- Nanolaminate facesheet
  - Multilayer metal foil, made by sputter deposition on a super-polished mandrel
- SiC substrate
  - Reaction-bonded Ceraform SiC is cast in a mold, fired, then bonded to facesheet
- Electroceramic actuators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

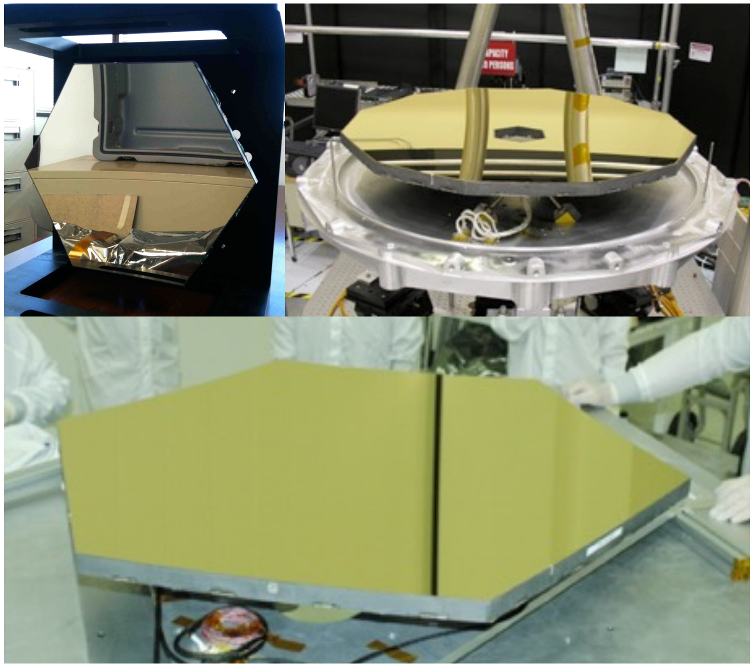
- Same SiC substrate
  - Cast to near-net shape, then rough ground
  - Large mirrors made by joining (brazing, e.g.) multiple segments
- Nanolaminate replaced by Silicon cladding
  - Low-stress Si deposited provides amorphous surface layer
  - Polishable to <5 Å microroughness
- Same facesheet actuators,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

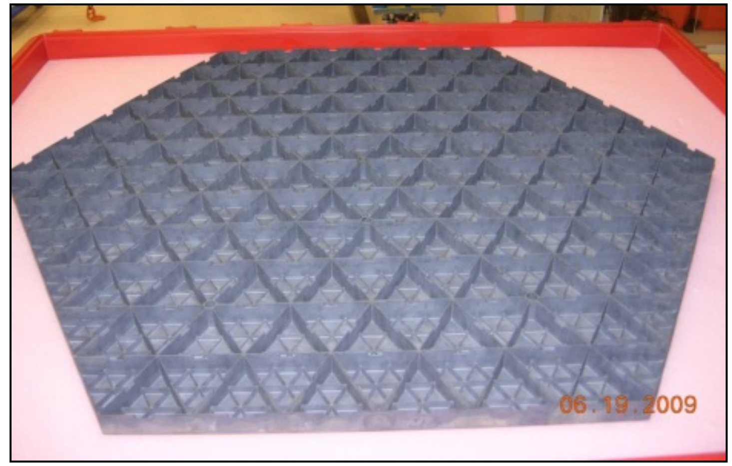
Actuated Hybrid Mirrors

Actuated Hybrid Mirrors (AHMs) provide an active mirror architecture

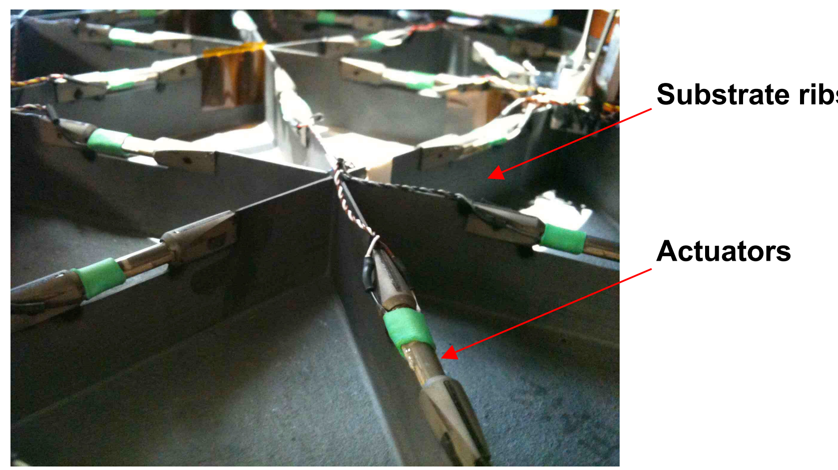


Unwin, S., et. al. (2010)

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



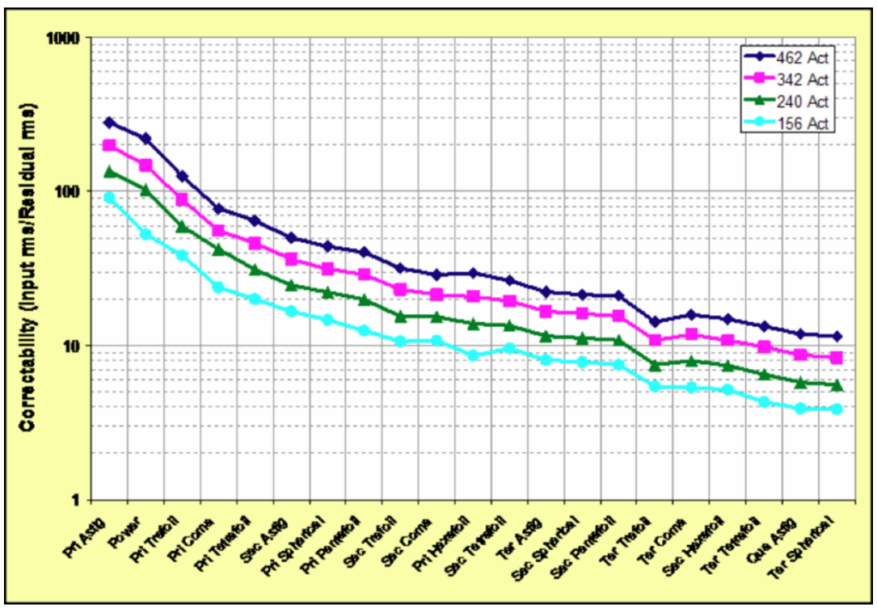
J. Wellman, G Weaver, D. Redding (2012), AAS Meeting 219-136.06



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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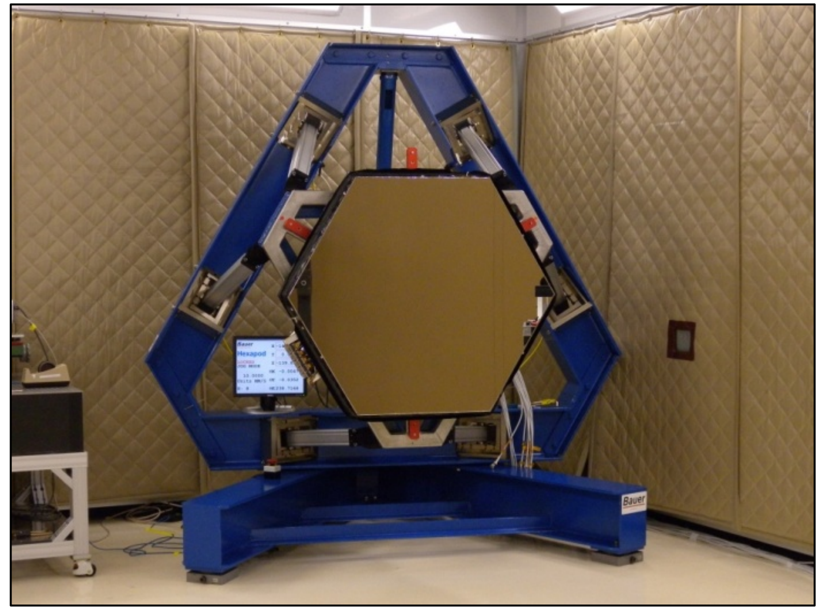
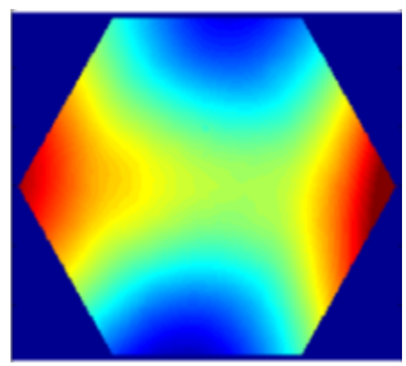
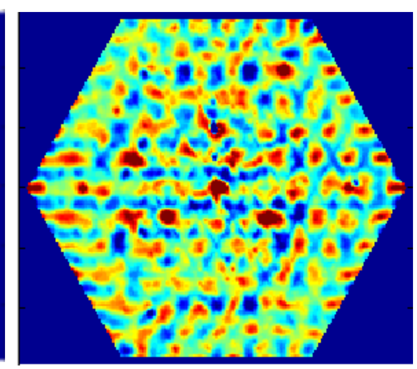


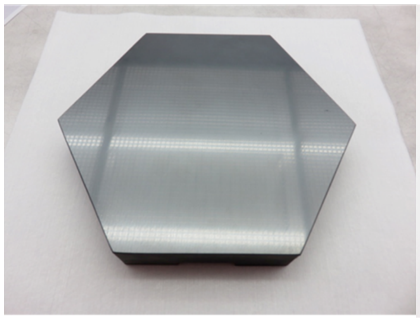
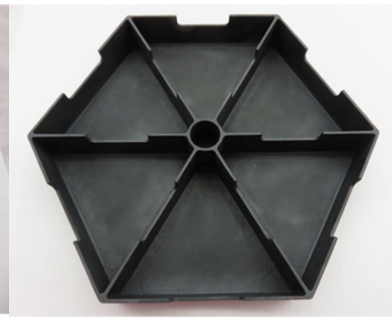
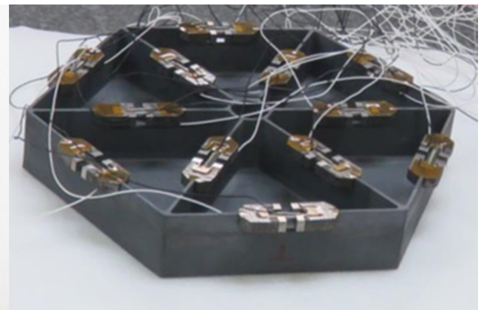


EM-4a Uncorrected
SFE = 1.88 µm RMS

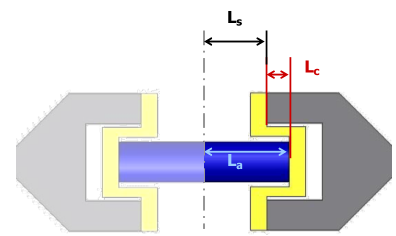


EM-4a Corrected
SFE = 0.014 µm RMS

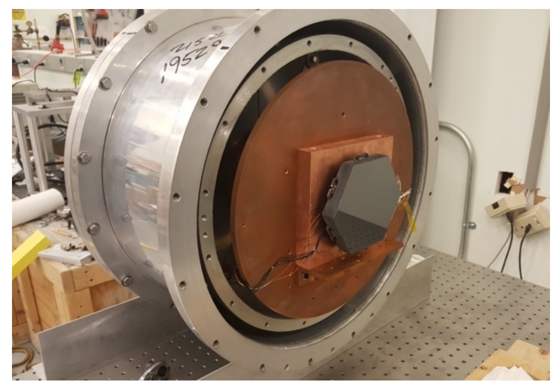
Cryogenic Active Mirror Demonstrator

“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



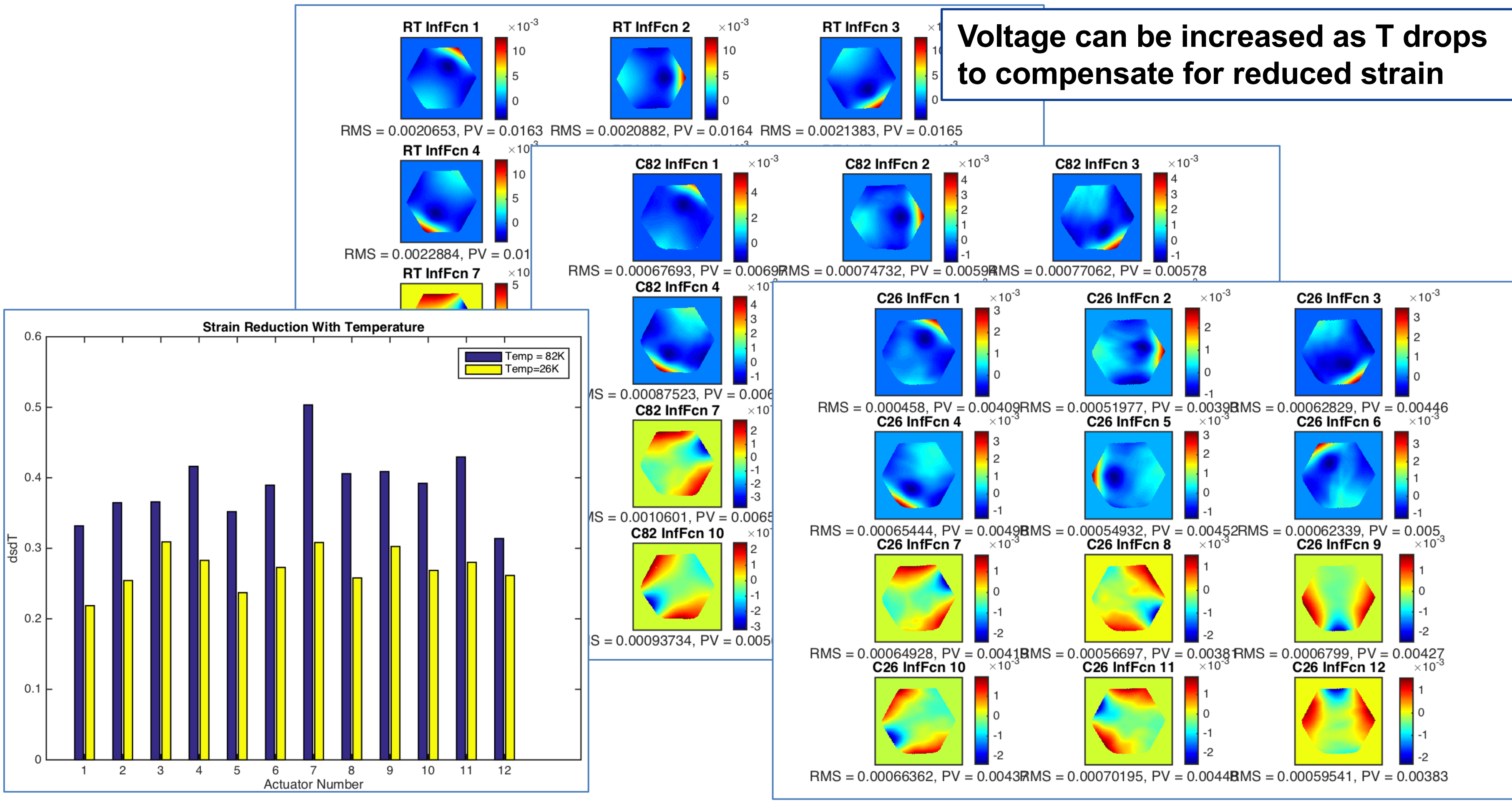
CAM established essentials for active mirror technology operating at cryo temps & FarIR wavelengths

JPL

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

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