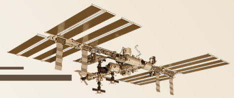


Enabling Space Telescope Technologies

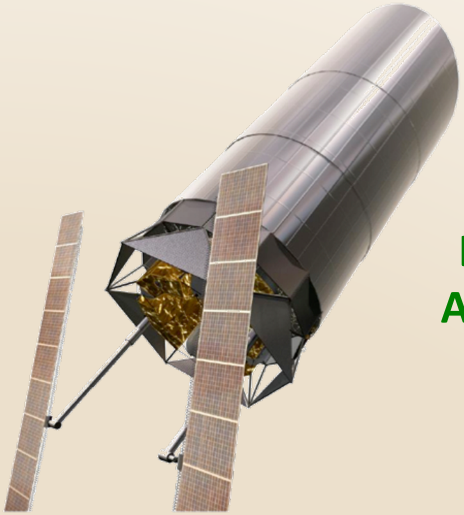
OPTIIX Technology Feed-Forward

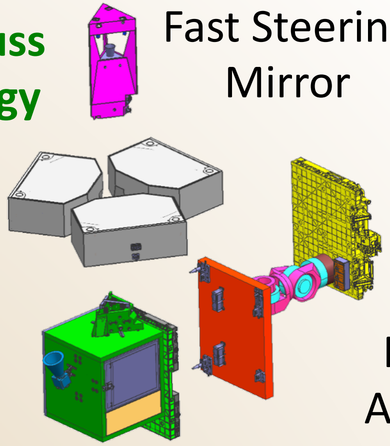
January 10, 2013

David Redding, Shanti Rao, Kent Wallace and Joseph J. Green

Jet Propulsion Laboratory, California Institute of Technology

OPTIIX Technology Feed-Forward





Laser Truss Metrology

Fast Steering Mirror

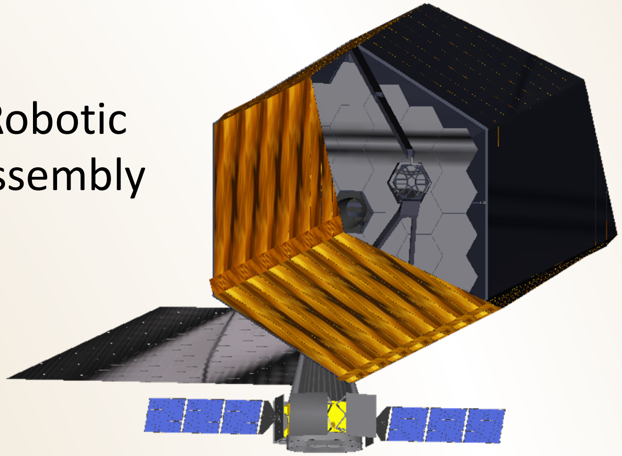
Lightweight Active Hybrid Mirrors

Precision Gimbal

Robotic Assembly

Wavefront Sensing and Control

Precision Latches



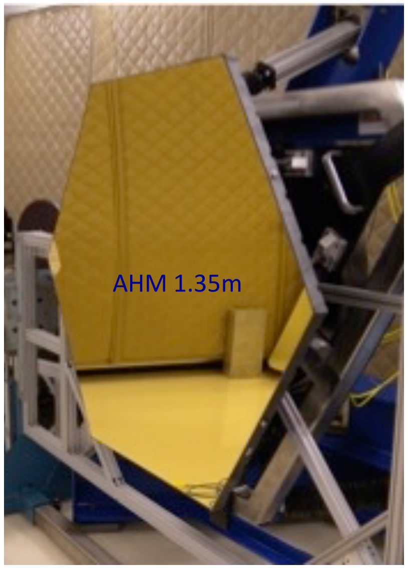
- OPTIIX assembly procedures and latching technologies will enable larger robotically-assembled space telescopes
  - These are not new technologies
- **OPTIIX Active Optics technologies** correct alignment and figure errors after assembly, from millimeter WFE to nanometer WFE
  - New technologies that can enable or benefit a range of space telescopes

OPTIIX Active Optics Technologies

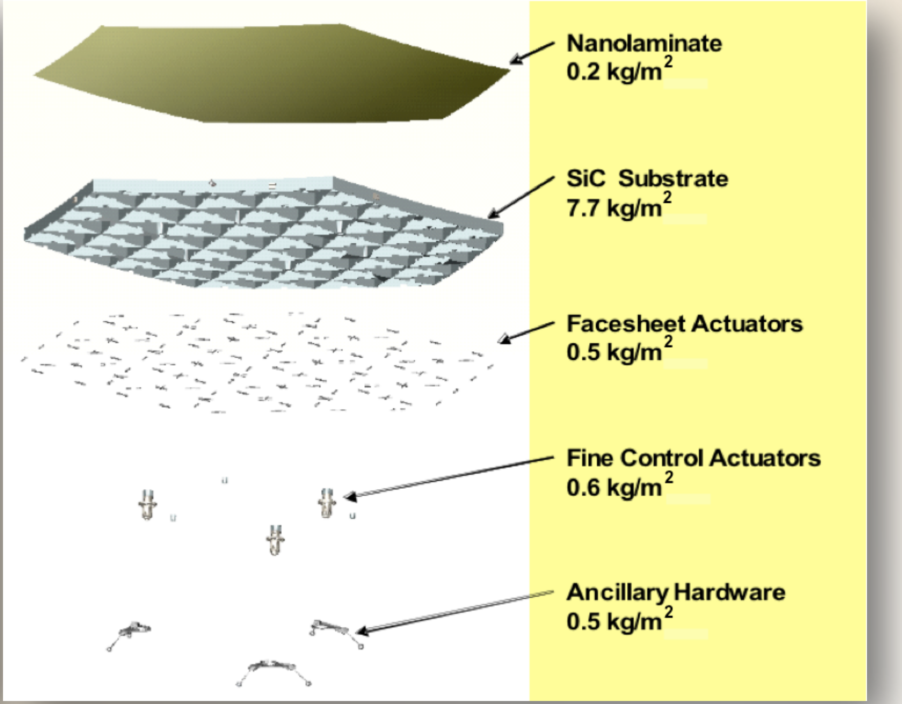
- OPTIIX Active Optics technologies:
    1. Lightweight Actuated Hybrid Mirrors (AHMs), with active thermal control
    2. Wavefront Sensing and Control
    3. Laser Truss Metrology
- Benefits for on-orbit assembled space telescopes
    - Corrects post-assembly optical errors, to achieve WFE of 10s of nanometers
- Benefits for space telescopes in general
    - Lower mass large optics, leading to lower mission mass and cost
    - Looser fabrication and alignment tolerances
    - Testable in 1g to 0g specs
    - Correct nearly any optical error after launch, reducing mission risk
    - Maintain optical quality in variable thermal conditions

Actuated Hybrid Mirrors (AHMs)

Actuated Hybrid Mirrors (AHMs)



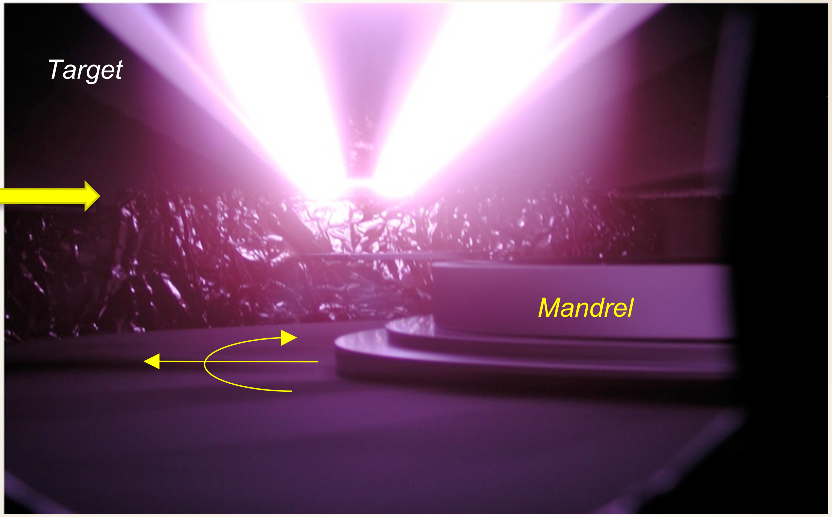
- Made by replication
- 0.5 to 1.35 m size demonstrated
- <14 nm rms SFE demonstrated
- <10 Å microroughness (projected)
- 10-15 kg/m² substrate
- <25 kg/m² total
- Active mirror
  - 37 to 414 actuators
  - Solid state, integrated into SiC substrate
- Testable in 1G to 0G specs

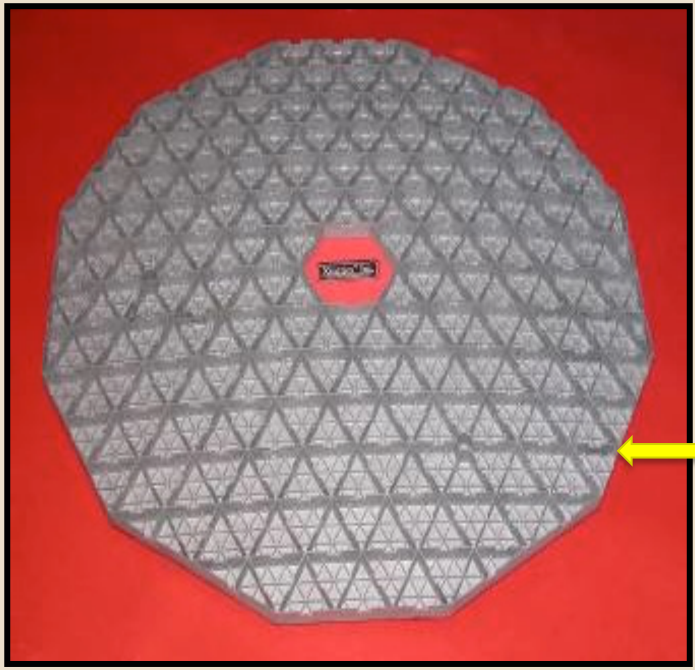


- Nanolaminate facesheet
  - Multilayer metal foil, made by sputter deposition on a super-polished mandrel
- SiC substrate
  - Reaction-bonded Ceraform SiC is cast in a mold, fired, then bonded to facesheet
- Electroceramic actuators
  - Surface-parallel embedded actuators give large stroke and high accuracy, by design
- Integrated closed-loop thermal control
  - Film heaters behind mirror keep figure constant

AHM Facesheet and Substrate

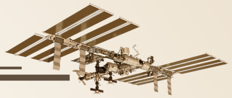
- Nanolaminates: multilayer solids with high interface concentration, developed at LLNL
- Nanolaminate foils are sputter deposited onto a nanoclean, superpolished glass mandrel
- Targets are switched to change materials
  - Au layer for AHM outer surface
  - 446 periods of:
    - 42 nm crystalline Zr layer
    - 3 nm amorphous Zr/Cu layer



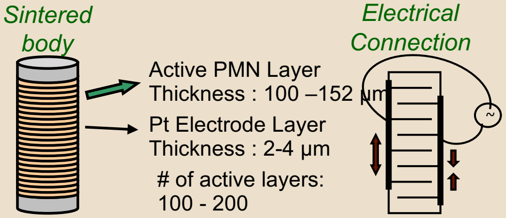


- Ceraform SiC: reaction bonded, low shrinkage Silicon Carbide, by Xinetics
  - Fugitive core foam mold created by CNC machining
  - SiC nanopowder slip fills mold
  - Part is freeze-dried, then mold core is leached out
  - First firing creates green state “prefired” part
  - Part is machined
  - Second firing to full hardness
- SiC has superior material properties

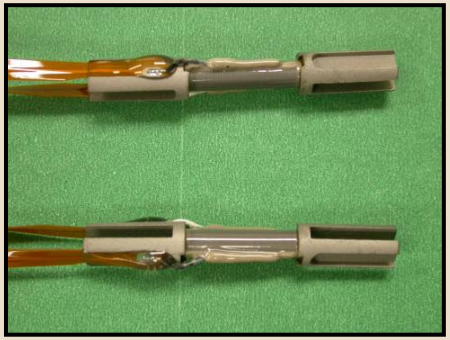
AHM Actuators and Integration



Robotic bonder

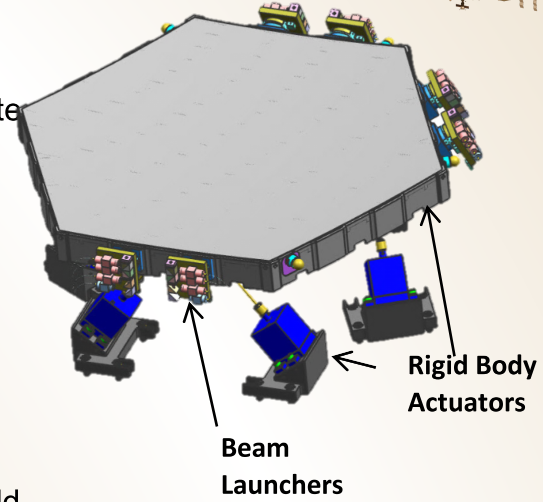


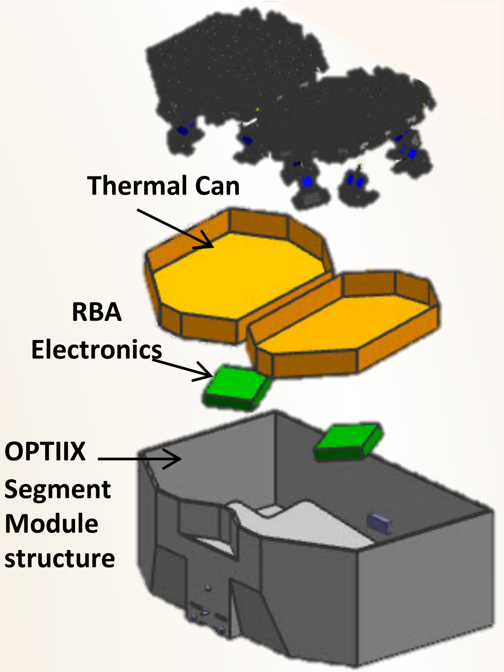
PMN actuator schematic



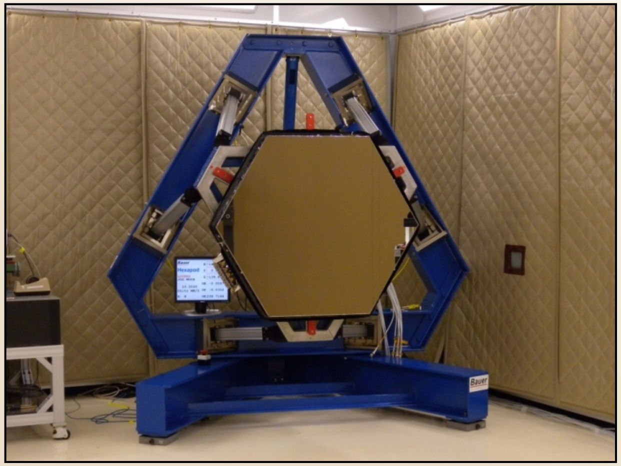
PMN actuators with titanium tabs for integration into SiC ribs

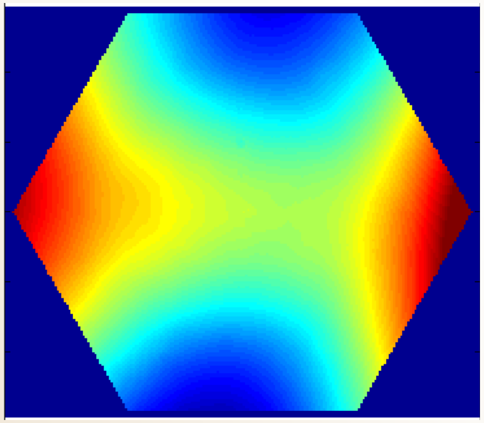
- SiC substrate is robotically bonded to nanolaminate on the mandrel
  - Epoxy fills in gaps between SiC and nanolaminate
- Mirror is released from the mandrel after cure
  - Mandrel is reused for other mirrors
- Xinetics actuators use PMN-PT electrostrictive ceramics
  - Multiple layers of ceramic and conductive electrode are co-fired to form a solid body
  - Used for AO deformable mirrors – many thousands used in observatories around the world
- High stroke, low voltage
  - ±2.5 um stroke at 20C
  - 0-100V operating rangeActuator integration
- Actuator tabs provide CTE-tailored interface to the SiC
  - Actuators bonded into cutouts in major ribs
  - Actuators powered to 50V during bonding and cure
  - Wires routed to connectors
- Mounts and thermal control hardware integration completes AHM integration



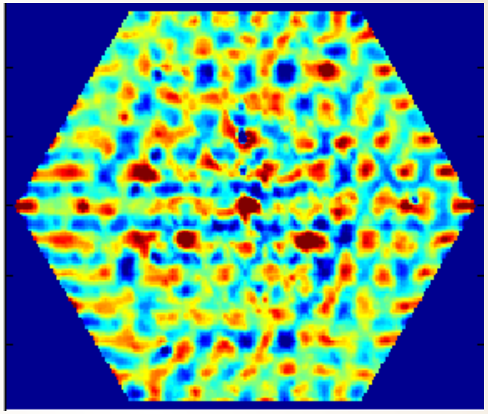


AHM Closed Loop Optical Performance



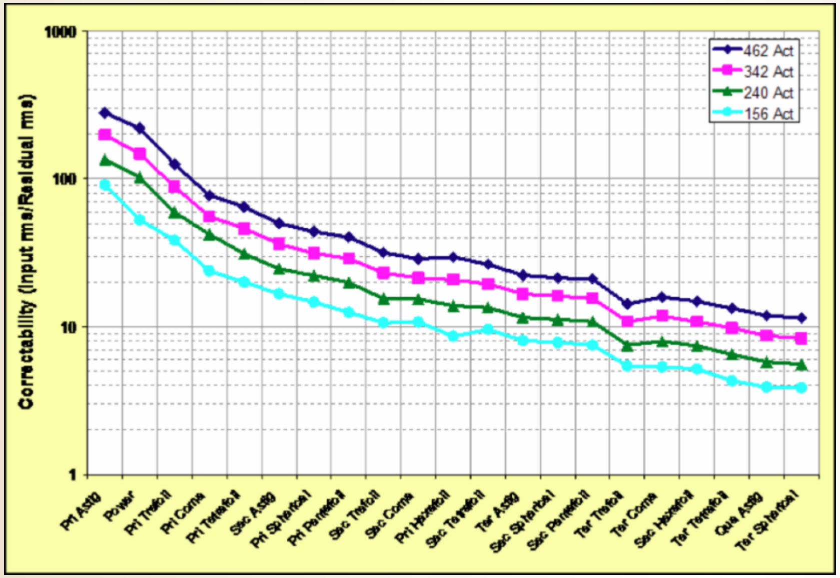


SFE = 1.88 µm RMS



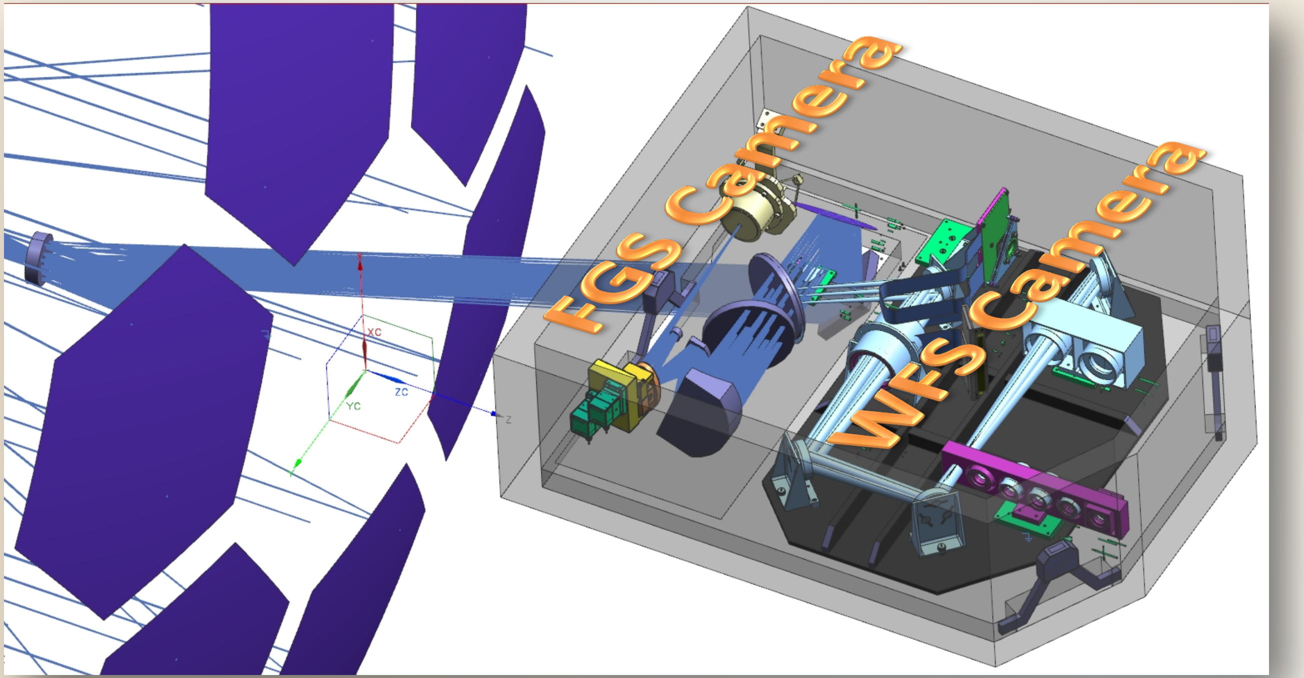
SFE = 0.014 µm RMS

- AHMs can meet stringent Astrophysics performance requirements
  - 14 nm RMS Surface Figure Error demonstrated
- AHMs can be significantly lighter than low-expansion glass
  - SiC is 5x stiffer and 8x stronger than glass
- AHMs mirrors are highly thermally controllable
  - SiC substrate is strong enough to use open-back structure, for direct thermal view factors into the ribs and facesheet
  - High thermal conductivity



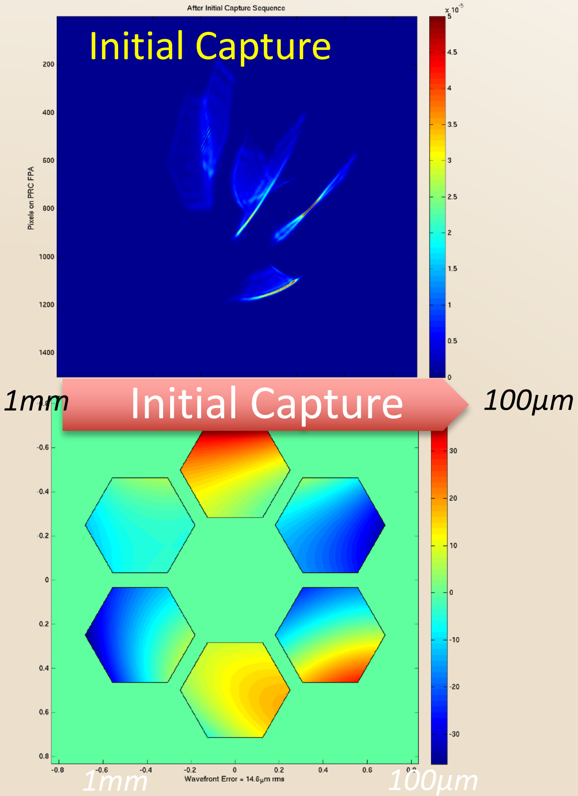
Wavefront Sensing

- *OPTIIX uses image-based Wavefront Sensing (WFS), while staring at a bright star*
- *WFS camera has selectable modes:*
  - **Shack-Hartmann Sensing** for initial segment alignment
    - *High dynamic range*
  - **Dispersed Fringe Sensing** for segment co-phasing
    - *Absolute piston sensor*
  - **Phase-Retrieval Sensing** for fine wavefront adjustment
    - *High accuracy (<5 nm) and high resolution (>1k × 1k)*
  - **Imaging camera**
  - **Internal calibration sources**



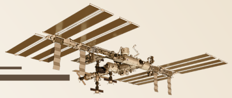
- *OPTIIX also uses a Fine Guidance System (FGS) camera, for line-of-sight stabilization*
  - Fast detector for 1kHz pointing error estimation
  - Steerable mirror for Guide Star acquisition

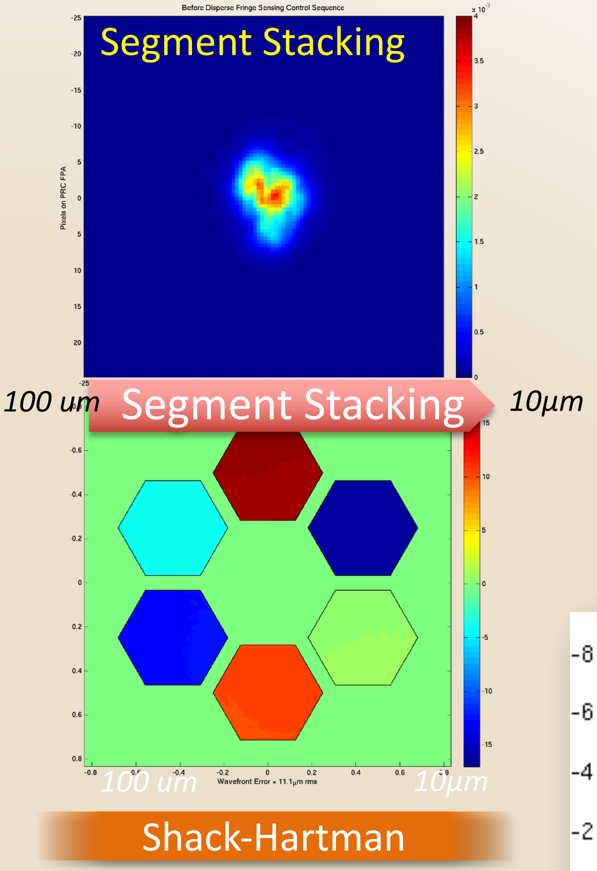
WFS&C: Initial Capture



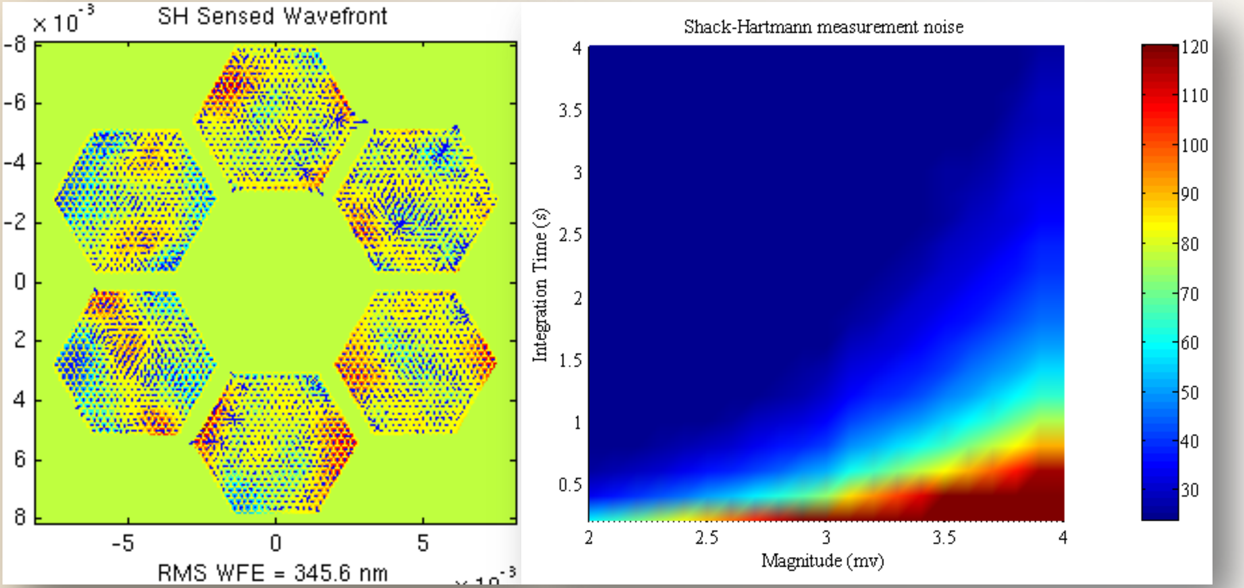
- Wavefront Sensing and Control (WFS&C) begins by pointing the telescope at a bright, isolated guide star
- ***Initial Capture*** operations scan each segment in tip and tilt, until the “spot” (subimage) appears on the WFS Camera focal plane
- WF error (WFE) is reduced from millimeters to 100 microns or so

WFS&C: Segment Stacking

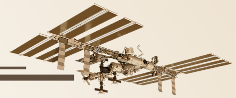




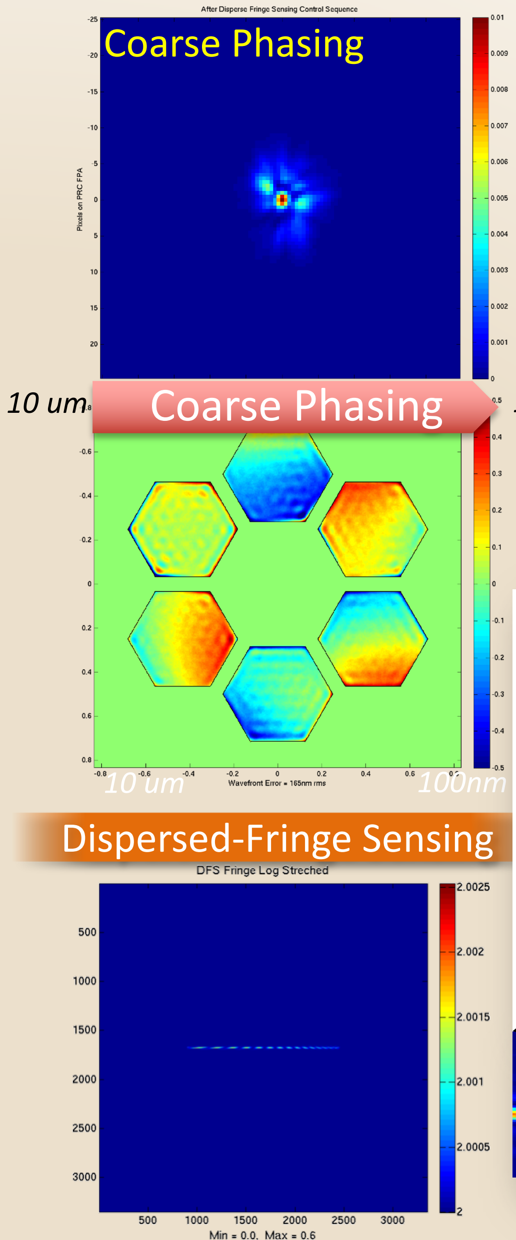
- ***Coarse Figuring*** operations uses the Shack-Hartmann Sensing mode of the WFS Camera to correct the segment figure errors
- *Figure error* component of total WFE is reduced from a few microns to under 100 nanometers
- ***Segment Stacking*** operations remove the tilt – but not piston – segment rigid body errors, by stacking the segment subimages in the center of the field

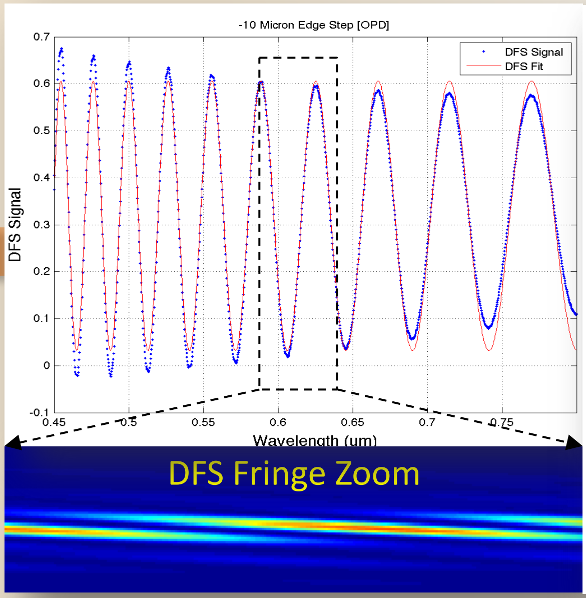


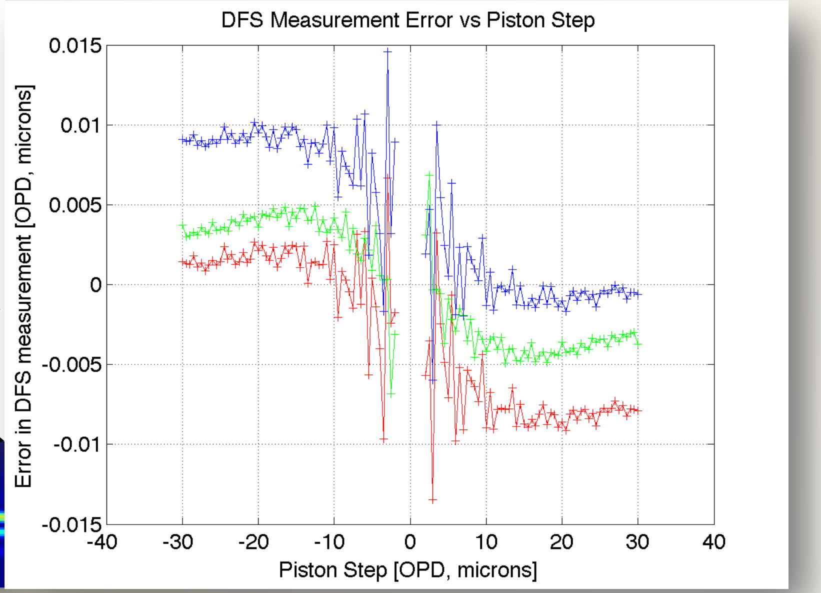
WFS&C: Coarse Phasing



- ***Coarse Phasing*** uses the Dispersed Fringe Sensing mode in the WFS Camera to generate interference fringes across segment pairs
  - A grism disperses the light from stacked pairs of segments, modulating the wavelength to find points where interference is constructive (peaks) or destructive (valleys)
  - Fringes are matched to a model to estimate piston error with high accuracy

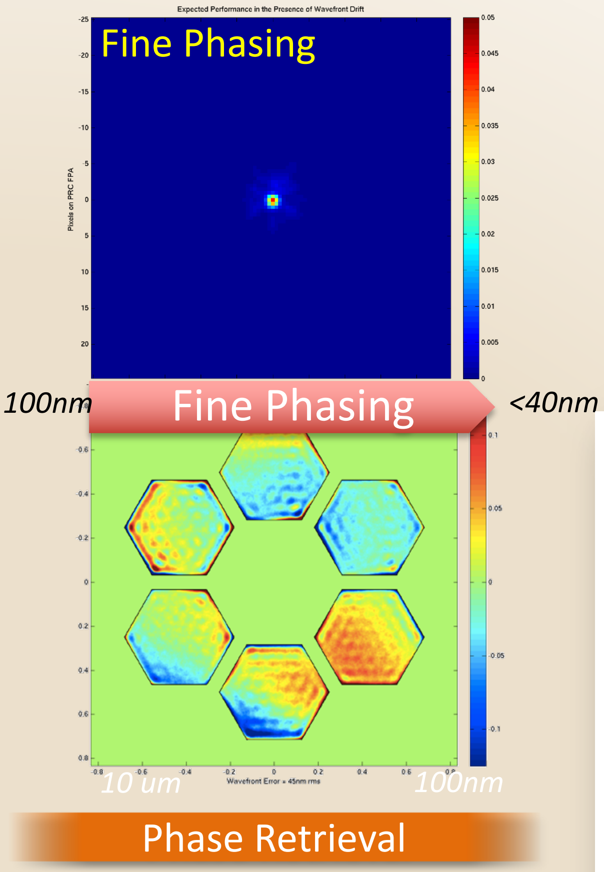


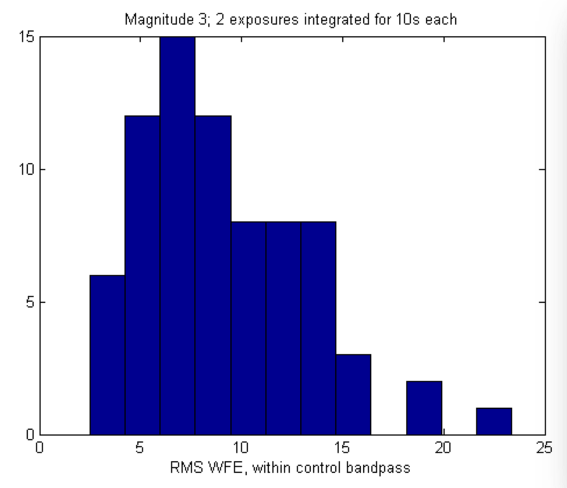


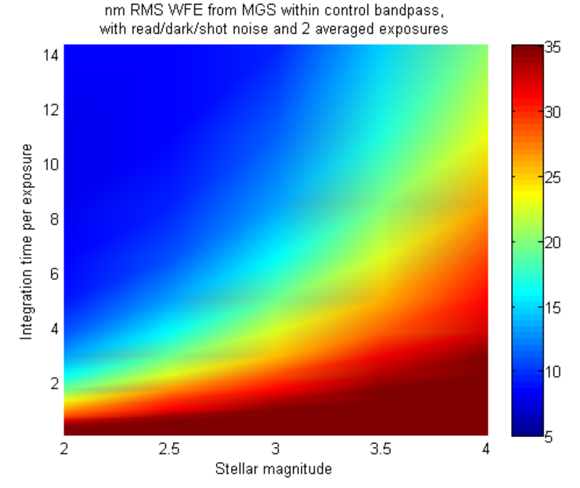


WFS&C: Fine Phasing

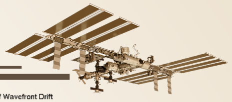
- ***Fine Phasing*** uses the Phase Retrieval mode in the WFS Camera to make high accuracy, high resolution WF measurements
  - Defocussed images of a star provide good SNR measurements of WFE
  - WF Control sets final figure and RB state

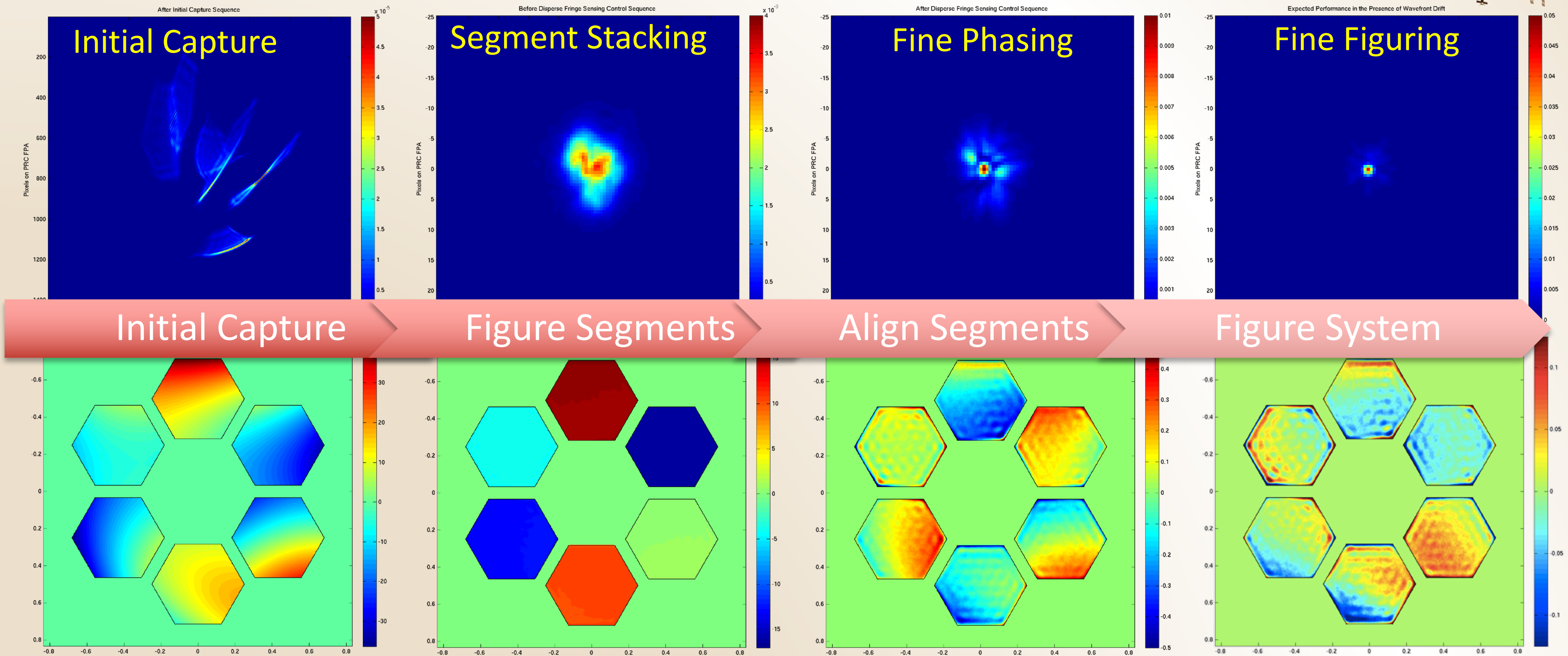






Wave Front Sensing and Control



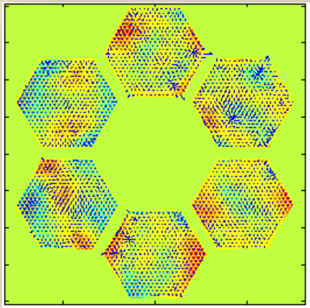


Initial Capture | Segment Stacking | Fine Phasing | Fine Figuring

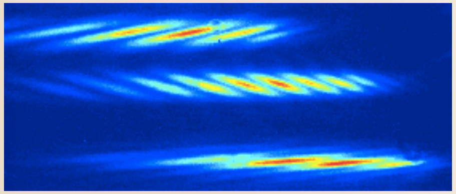
Initial Capture → Figure Segments → Align Segments → Figure System

1mm *100µm* *10µm* *1µm* *100nm* *10nm* *RMS WFE*

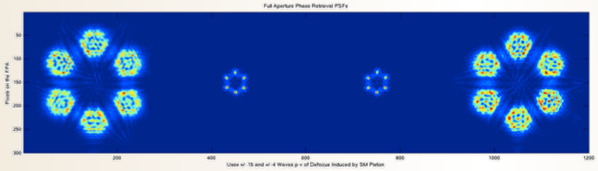
Shack-Hartman



Dispersed Fringe Sensing

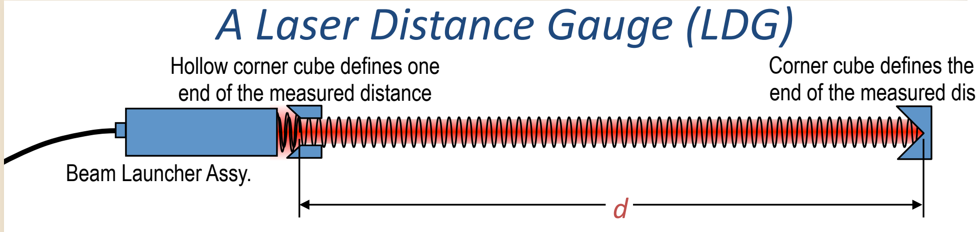


Phase Retrieval



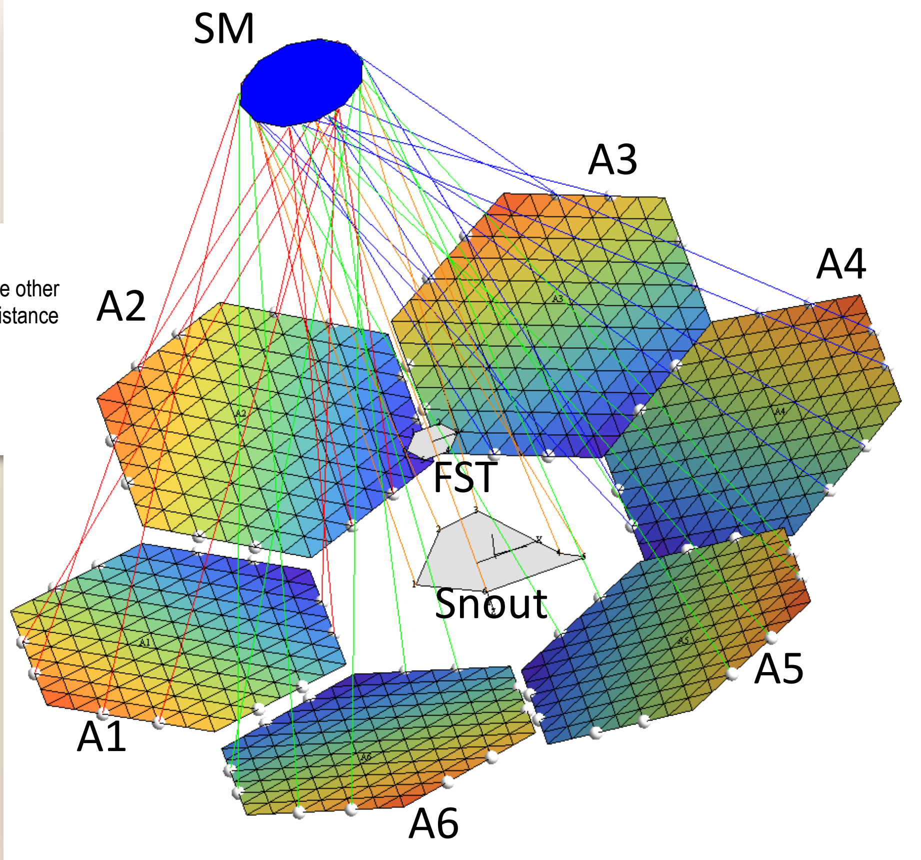
Laser Metrology

- 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



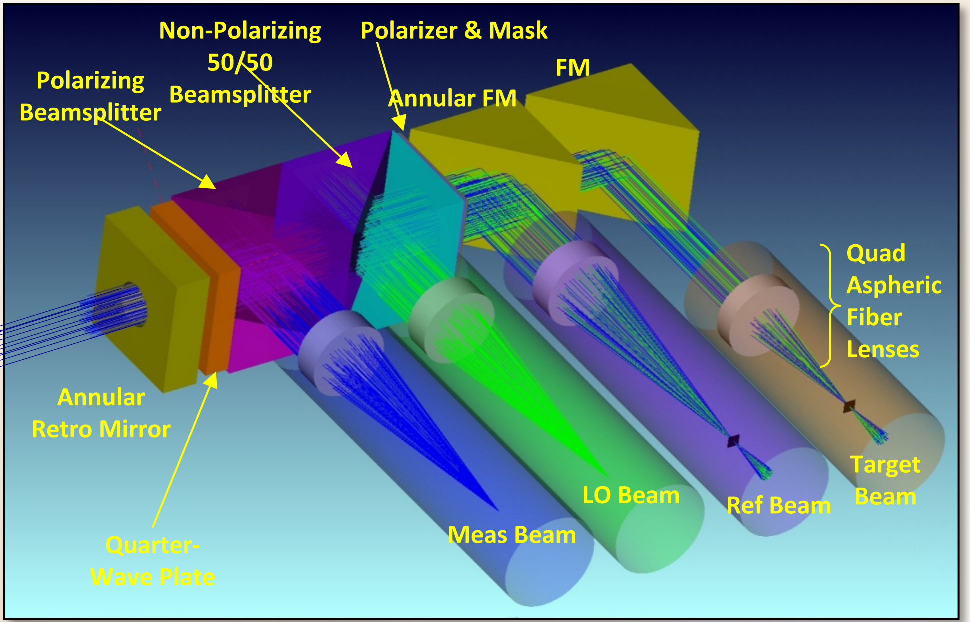
A Laser Distance Gauge (LDG)

- 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%)

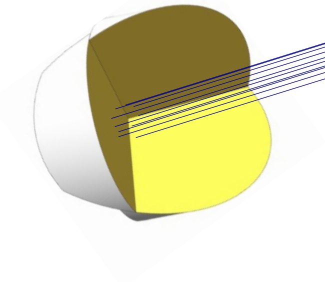


OPTIIX Laser Metrology

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

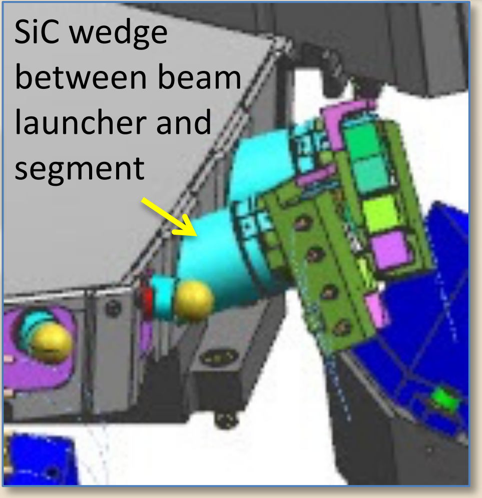


Corner cube on SM



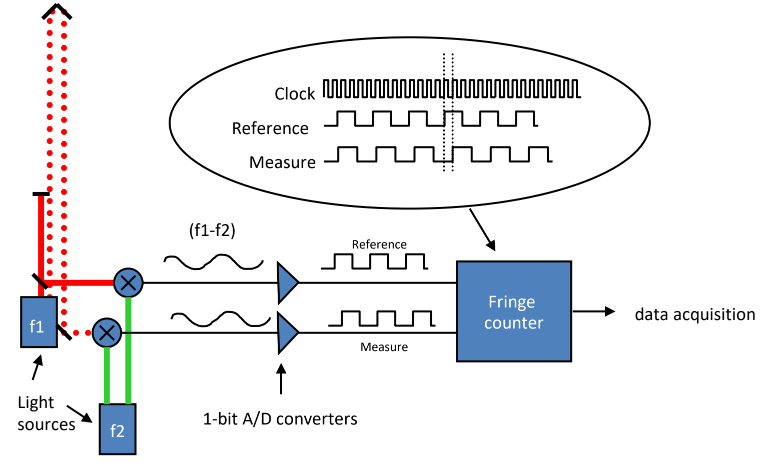
Metrology error multiplier
4.7 nm rms WFE / nm rms

Segment temperature
error multiplier
130 nm rms WFE / K rms

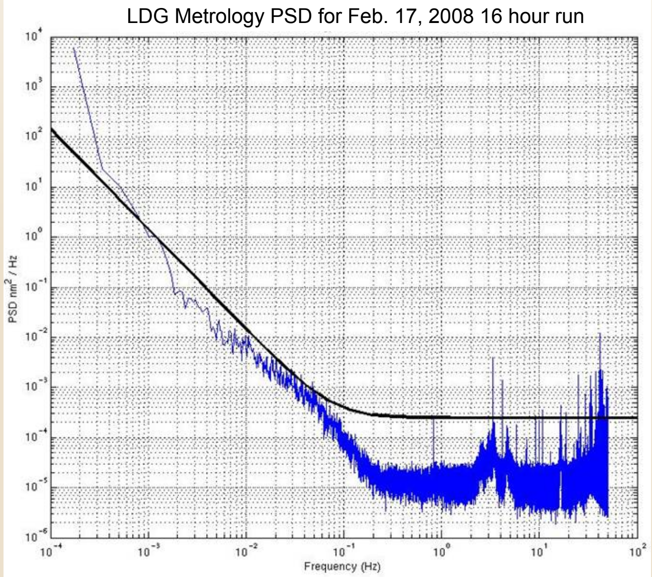


SiC wedge between beam launcher and segment

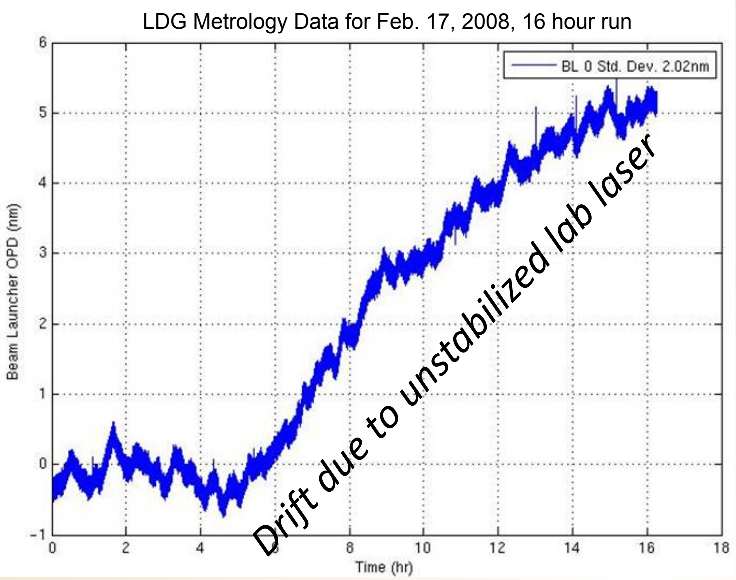
Common-path heterodyne interferometer



Metrology Performance



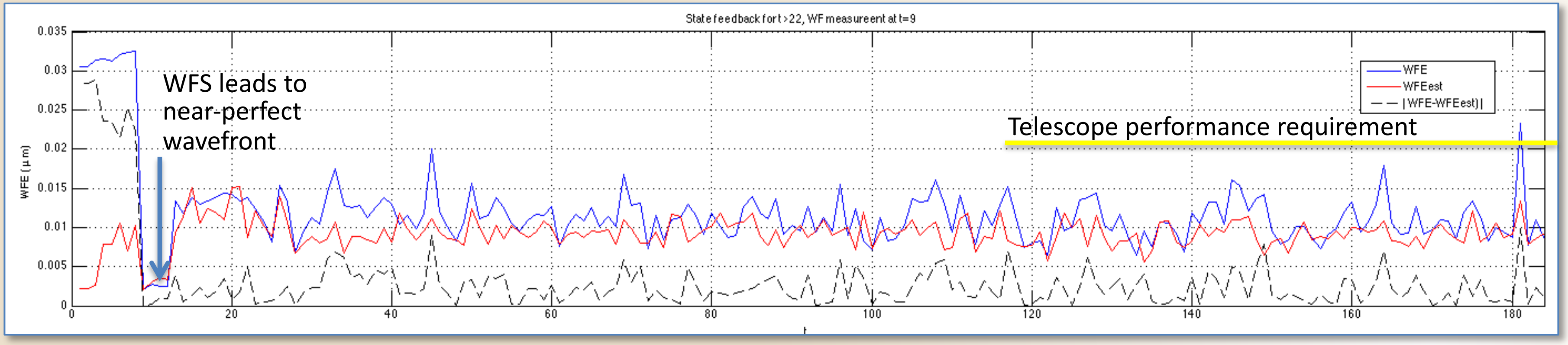
LDG Metrology PSD for Feb. 17, 2008 16 hour run



LDG Metrology Data for Feb. 17, 2008, 16 hour run

Drift due to unstabilized lab laser

- LDG measured performance meets requirements



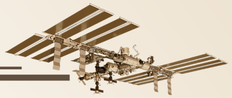
State feedback for t>22, WF measureent at t=9

WFS leads to near-perfect wavefront

Telescope performance requirement

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

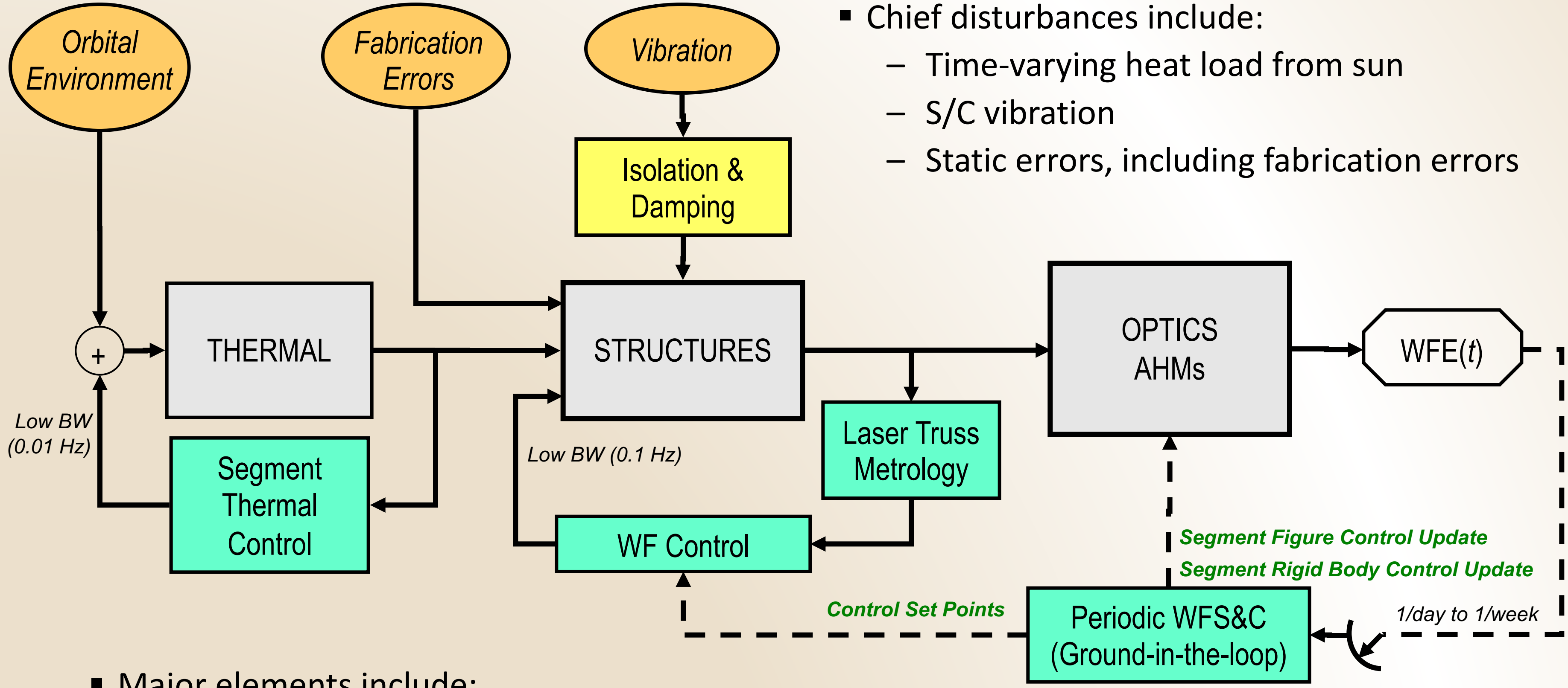
Benefits of Active Optics



- Required for on-orbit assembled telescopes, to correct expected large WFE
- Passive telescopes have had mission-threatening optical errors; HST is a good example, with 250 nm uncorrected WFE
  - Active mirrors offer correctability without astronaut servicing
- Reduced mission risk
  - Active SSMs or AHMs can correct nearly any optical errors that might arise on orbit to *assure* mission performance
  - SiC materials are more resilient than glass, lowering risk of failure
- Improved testability
  - Active SSMs or AHMs enable testing to spec during system assembly and integration, without backouts, even in 1 G
- Reduced mission cost
  - By reducing mission mass
  - By relaxing assembly tolerances
  - By speeding up I&T
  - By reducing mirror cost

Backup

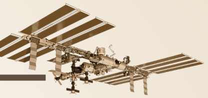
Active Optics Block Diagram

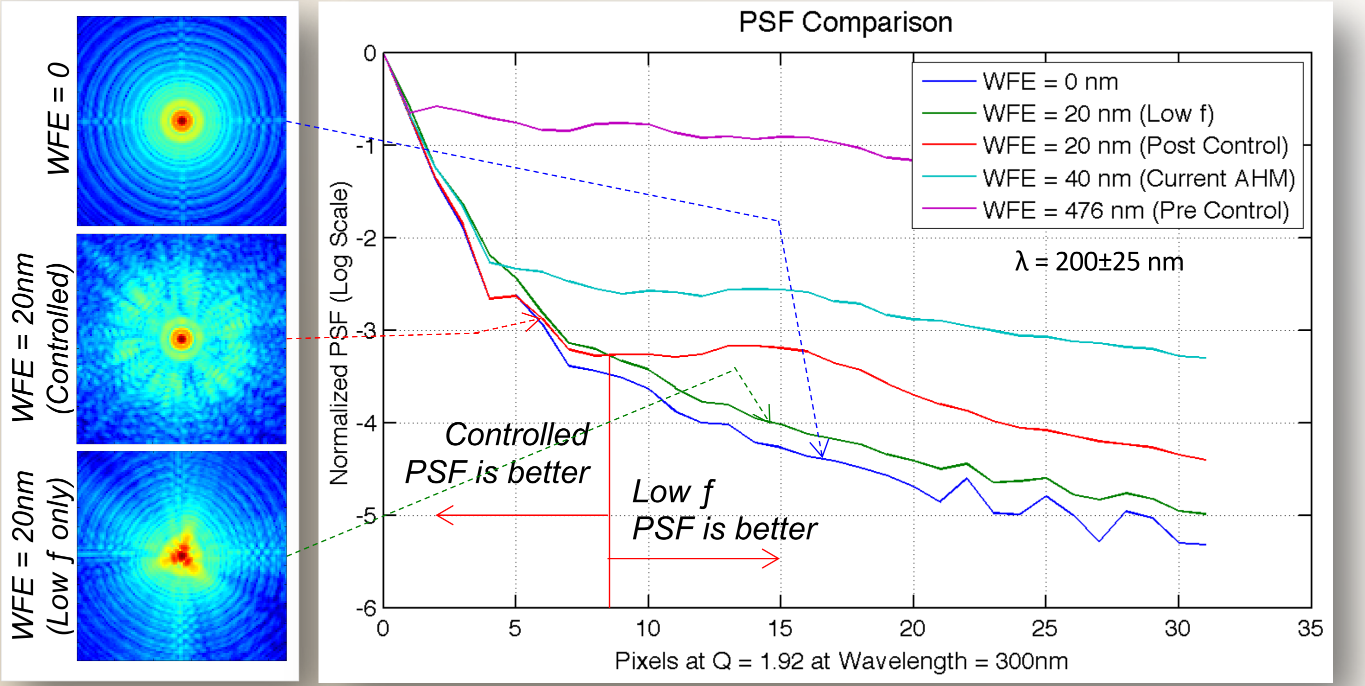


- Chief disturbances include:
  - Time-varying heat load from sun
  - S/C vibration
  - Static errors, including fabrication errors

- Major elements include:
  - Laser Truss Metrology WF control to stabilize alignments
  - Segment Thermal Control to stabilize optical figure
  - Periodic Wavefront Sensing and Control to update control setpoints
  - Isolation and Damping to attenuate vibration disturbances

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. *f* 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