Active Optics for UV/Vis/IR Space Telescopes

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Sept 22, 2011

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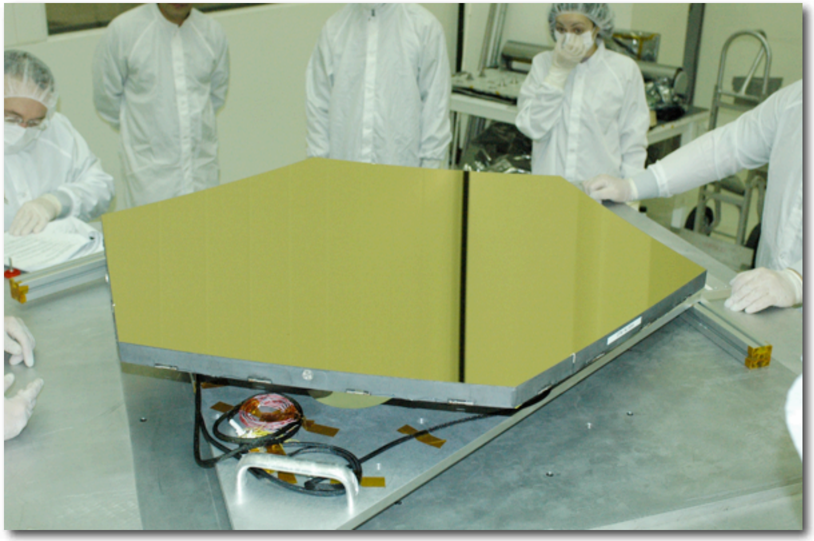
This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology,
under contract with the National Aeronautics and Space Administration.

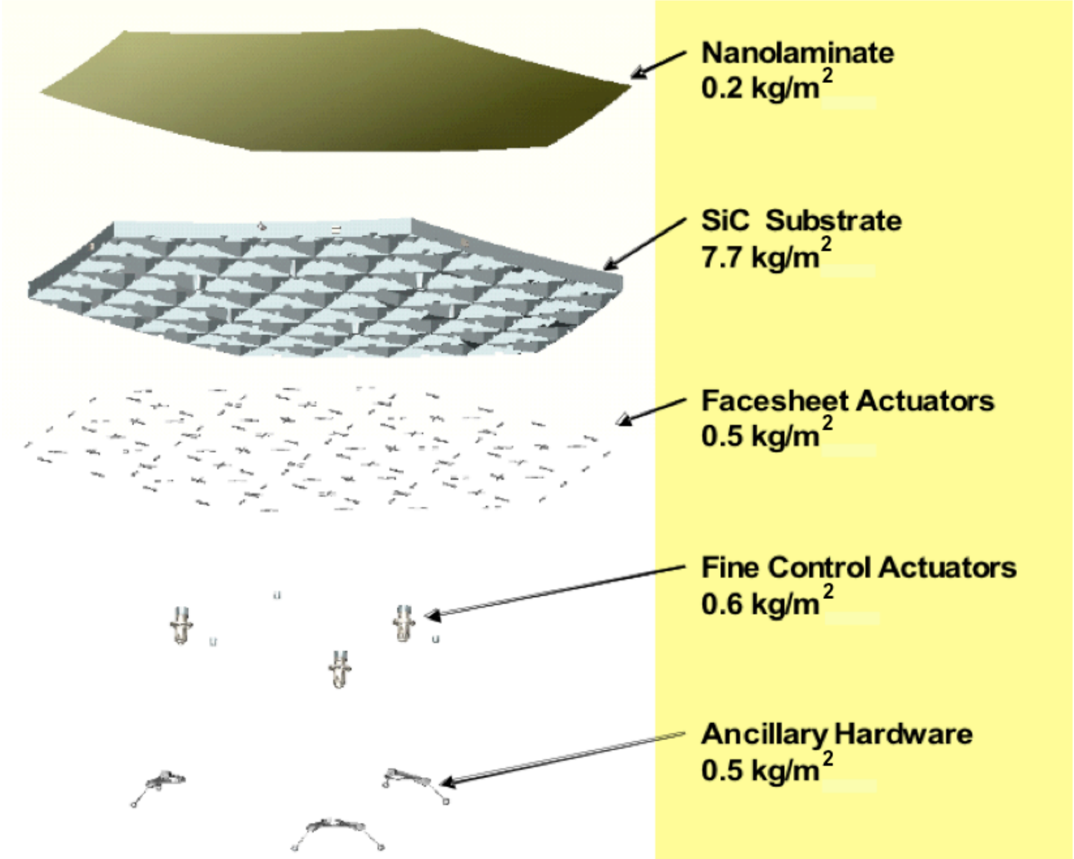
Active Optics for Space Telescopes



- **Active Optics: Mirrors that can be reshaped after launch; and the Wavefront Sensing and Control system to command them**
  - *Reduce mission risk*
    - Correct any optical problem that might arise
    - Enable testing to spec during system assembly and integration
  - *Reduce mission cost*
    - Reduce mission mass
    - Relax fabrication and assembly tolerances
    - Speed up Assembly, Integration and Test phases

Actuated Hybrid Mirrors (AHMs)

- **AHMs are large mirrors**
  - PMs or PM segments
- **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



- **AHMs are *low mass* and *high strength***
  - Areal density < 20 kg/m^2 including electronics for meter-class AHMs
- **AHMs are *made by replication* for high optical quality and low cost**

Polished SiC Mirrors

Polished SiC mirrors are AHMs without a bonded Nanolaminate facesheet

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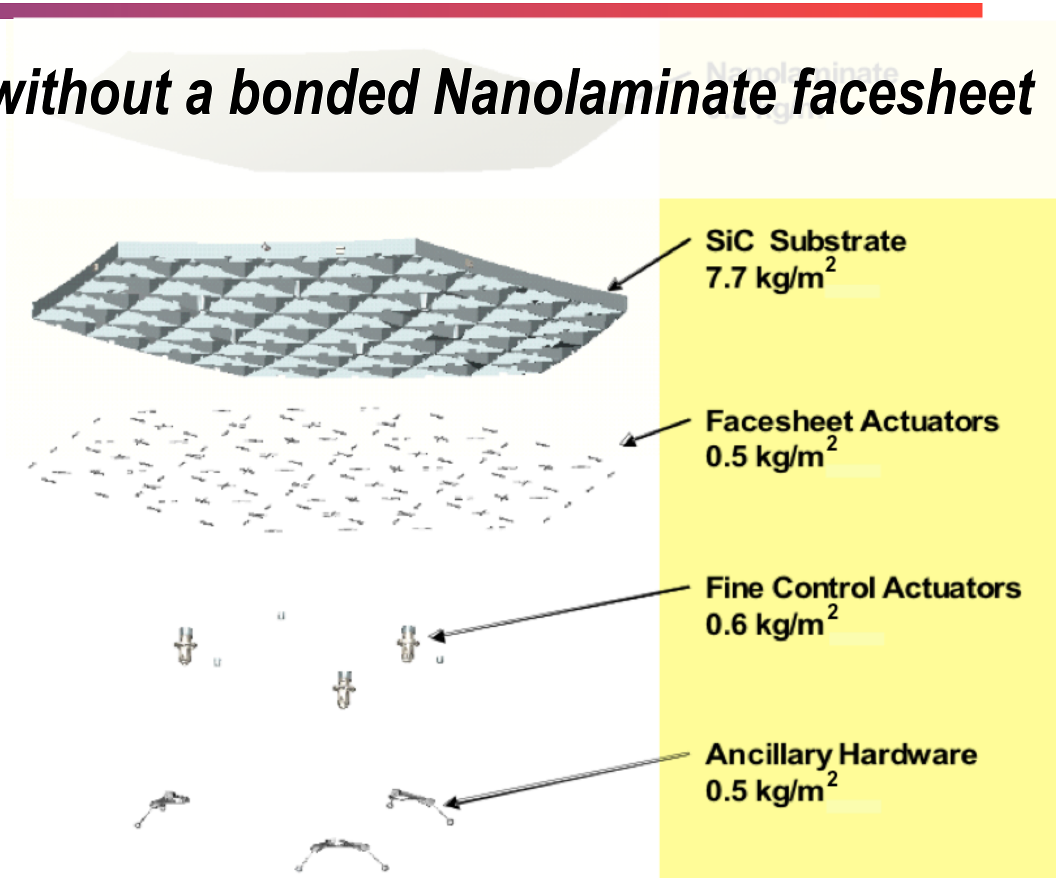
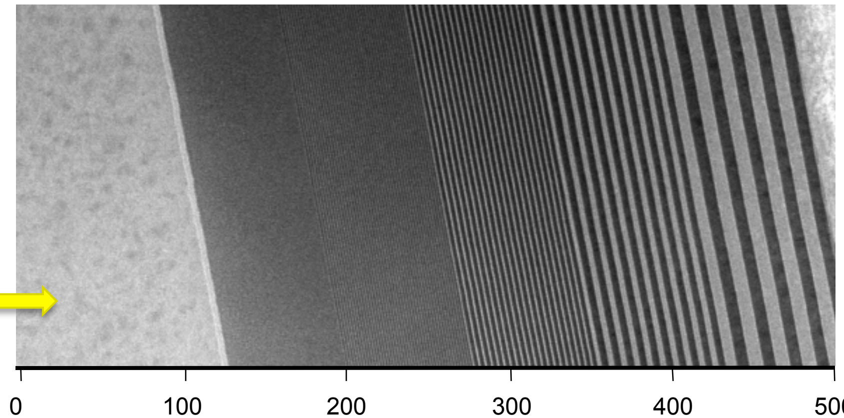


- **Polished SiC mirrors are also low mass and high strength**
- **Polished SiC mirrors can be joined to create very large mirrors**
- **Polished SiC mirrors can be used at cold or even cryo temperatures**

Nanolaminate Properties

- **Nanolaminates: multilayer solids with high interface concentration**
  - Have been made from 72 materials
  - Amorphous/crystalline layers for AHM
- **X-ray optic example has layer thicknesses from 0.4 nm to 32 nm**



- **AHM nanolaminate layers:**
  - A few Å of C for release layer
  - Au layer for outer surface
  - Conventional coating applied
  - 446 periods of:
    - 42 nm crystalline Zr layer
    - 3 nm amorphous Zr/Cu layer
- **Finished 1.52 m nanolaminate being removed from chamber**

Ceraform Silicon Carbide

- **Ceraform SiC:**
  - Fugitive core foam mold created by CNC machining
  - SiC nanopowder slip fills mold
  - Part is freeze-dried
  - Mold core is leached out
  - First firing creates green state part
  - Part is machined
  - Second firing to full hardness
- **Final rough grind of SiC front surface matches the curvature of the mandrel/nanolaminate to ± 5 μm**

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
$\Delta\alpha$ 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
$K/\alpha E$, Thermal Stress	MW-m/N	101	63	140	646	High

Typical finished substrate

Joined SiC Mirrors

- **SiC substrates can be joined using brazing or bonding techniques, and then polished, to make very large, active mirrors**
  - 4 m or larger, using existing SiC fab infrastructure
  - Directly polished to <20Å surface roughness
  - Superpolishable to <5Å after Si cladding
  - With or without central hole
  - Can be used at cold temperatures

AHM and SiC Mirror Technology Status

- **AHM mirror technologies are maturing rapidly**
  - To do: grow to larger sizes (1.8m, 2.5m, e.g.)
- **Very large polished SiC mirrors offer benefits in some cases**
  - Large monolithic primary mirrors (4m or larger)
  - Cold or cryogenic mirrors, active or not
- **Very large polished SiC mirrors require some further technology development**
  - To do: Lightweight mirror segment joining
  - To do: Low-stress Si cladding
  - To do: Superpolishing
  - To do: Cryogenic active mirrors, using actuators to correct cool-down stresses and avoid costly cryo-null figuring
- **Other active optics technologies needing development**
  - To do: “Self-sensing” for <10pm WFE stability
  - To do: Continuous, pm accuracy WFS for internal coronagraph or lensing applications

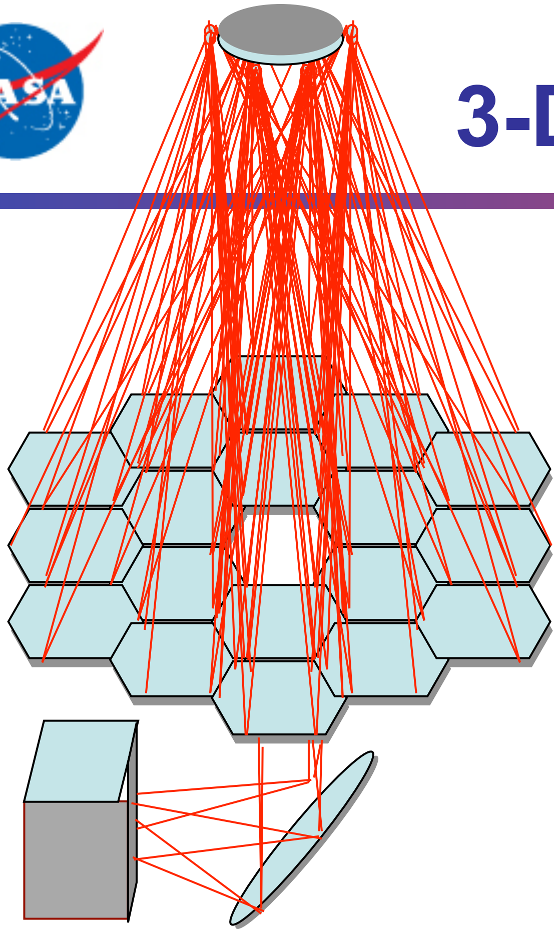
Wavefront Sensing and Control

- **Wavefront sensing and control methods are well established**
  - JWST
  - Active mirror testbeds

- **Proposed exoplanet-specific WFSC methods need further development**
  - Continuous pm-level WFS
  - Mirror self-sensing methods

- **(Details in backup charts)**

3-Dimensional Laser Truss

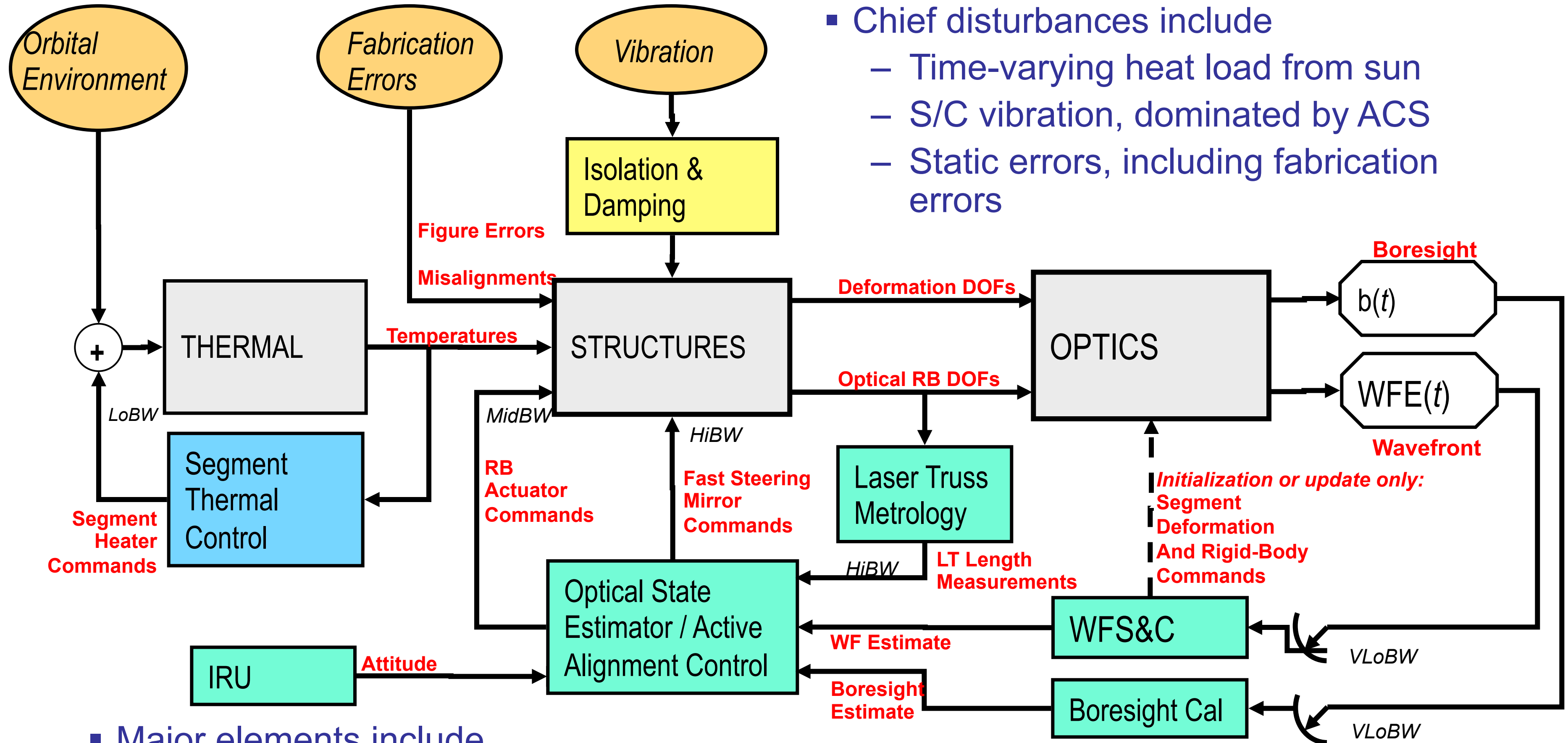


- **Uses Laser Distance Gauges (LDG)**
  - 6 LDGs per segment measure all relative RB DOFs in the entire OTA
    - All PM segments, the SM, FF, TM and OBA
  - The IRS is attached to the OBA, providing measurements of 6 more absolute DOFs wrt inertial space
- **Same measurement equation:** $\delta = Cx$
  - Sensitivities computed from model kinematics

- **Measurement is invertible:** $x = C^{-1}\delta$ **is full rank**
- ***Optical State Estimator*** **uses a Kalman Filter to estimate the RB state**
  - Balances measurement vs. prior knowledge for optimal estimate
  - Predicts WF and Boresight from state estimate
- **Feedback control using RB actuators and optimal control laws keeps performance in spec**
  - Integrated model will be used to evaluate performance

Block Diagram

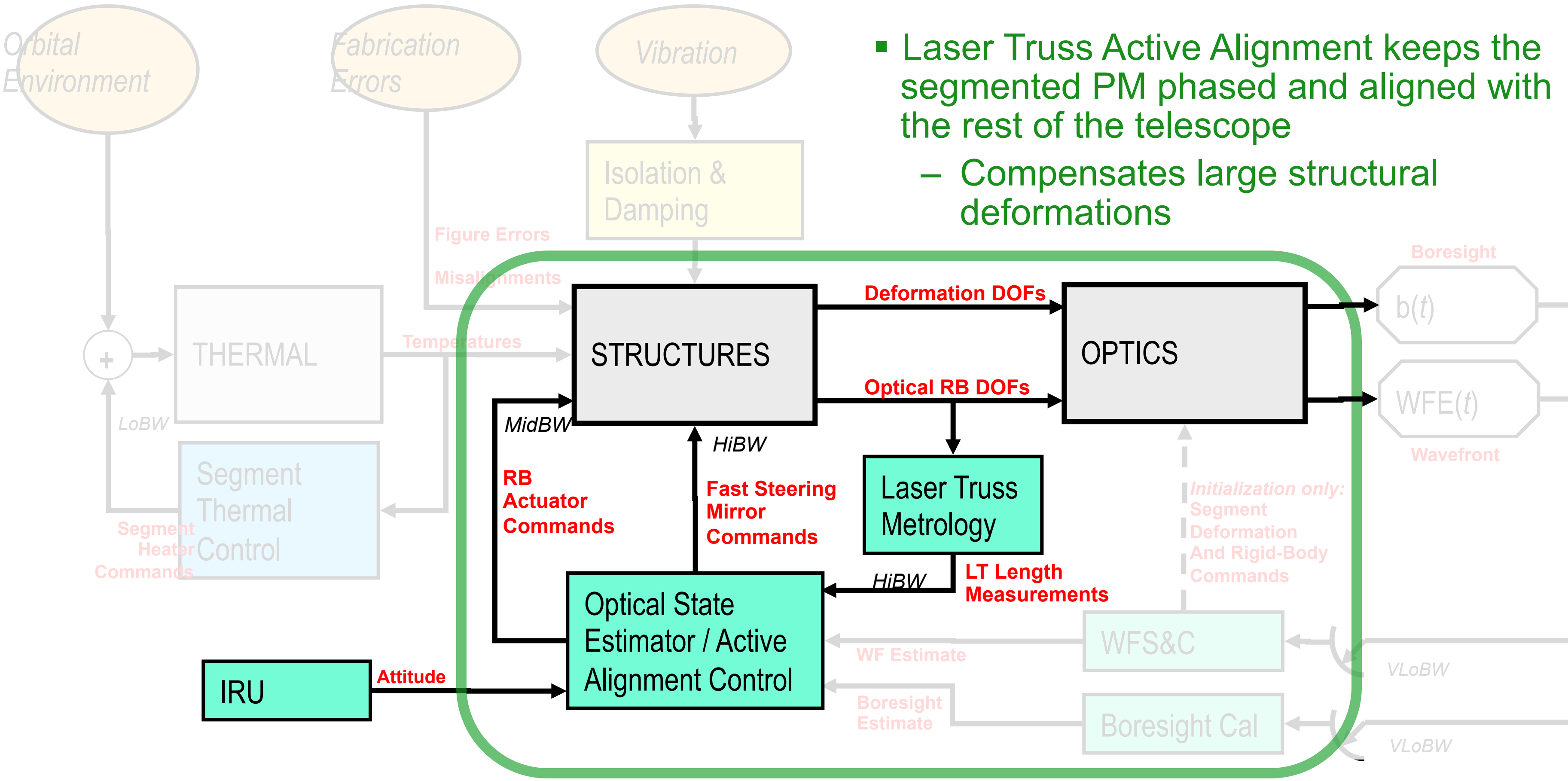
- Chief disturbances include
  - Time-varying heat load from sun
  - S/C vibration, dominated by ACS
  - Static errors, including fabrication errors



- 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

Laser Truss Keeps All Optics Aligned

- 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 a Kalman Filter to estimate the perturbation state of all the optics
- Estimated state is fed back to control WFE at low BW and boresight at high BW

Laser Truss Pros and Cons

- **Pros**
  - High accuracy – < 1 nm per LDG when Δ angle is small
  - Observes all important RB states – including Primary and Secondary Mirrors, and Optical Bench
  - Low drift – with 1 laser feeding all LDGs, require WFS update once per day
  - Light weight beam launchers
  - No on-segment power dissipation
  - Does not require segments to be close together
  - Does not require any particular gap geometry
  - Works with missing segments (no degradation for the segments that remain)
  - Useful for I&T
  - Degrades gracefully if individual LDGs go out
- **Cons**
  - Requires 12 fibers into each segment for 6 DOF

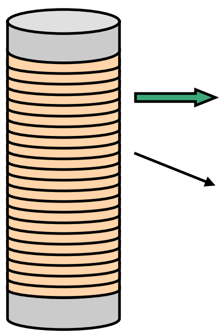
Conclusion

- **AHMs provide high-quality, low-mass large optics**
  - Polished SiC mirrors promise the same advantages for very large mirrors, or cold mirrors
- **Active optics compensate typical space telescope errors to reduce mission risk and cost**
  - 10x to 300x for low-order errors, depending on actuator count
- **Active optics relax fabrication and assembly tolerances system-wide, lowering cost**
- **Active optics permit testing to spec performance on the ground, at multiple stages of assembly, without complex GSE**

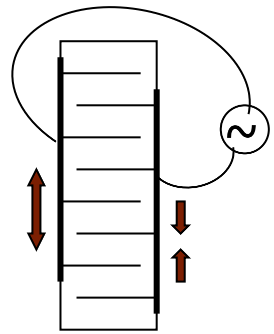
BACKUP

Actuators

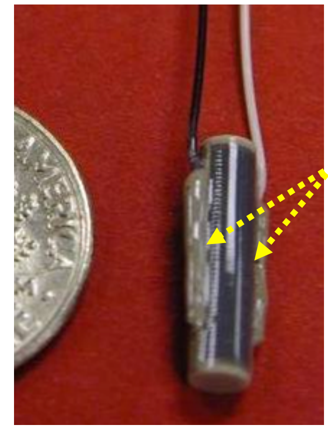
Sintered body



Electrical Connection (conceptual)



XiRE 0313 Photo, XiRE 0416 similar



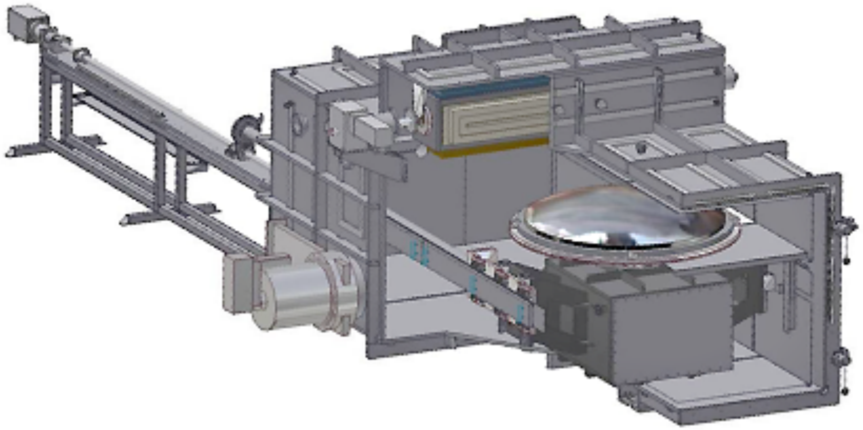
- **NGX actuators use PMN-PT electrostrictive ceramics**
  - Multiple layers of ceramic and conductive electrode are co-fired to form a solid body
  - Conductive polymers for external electrode and wire bonding (no soldering)
  - Conformal insulating polymer coating

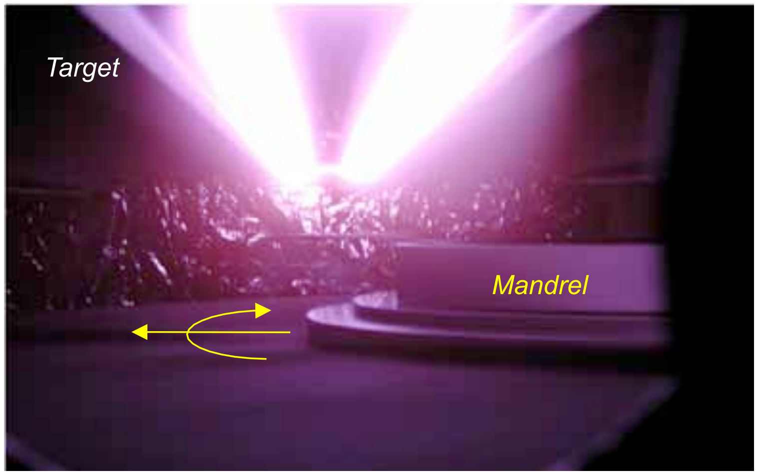
- **High stroke, low voltage**
  - ±2.5 um stroke at 20C
  - 0-100V operating range
- **Used for astronomical Deformable Mirrors**
  - High reliability

Actuator with Mounting Tabs

Nanolaminate Facesheet

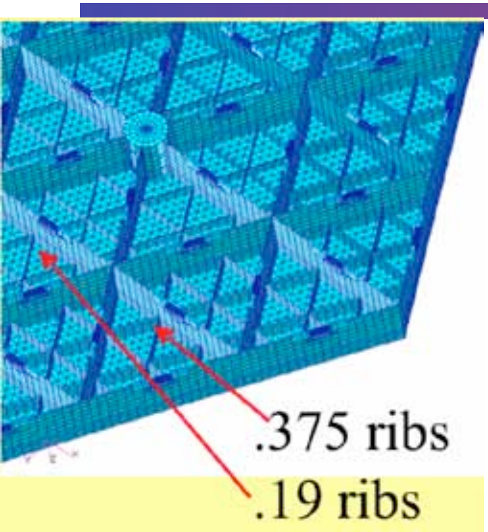
- AHM nanolaminates are made at LLNL, in the Very Large Optic Coater (VLOC)
- Mandrel is a nanoclean, superpolished glass tool with figure opposite to final AHM
- Mandrel is translated and rotated under "targets:" the deposition sources





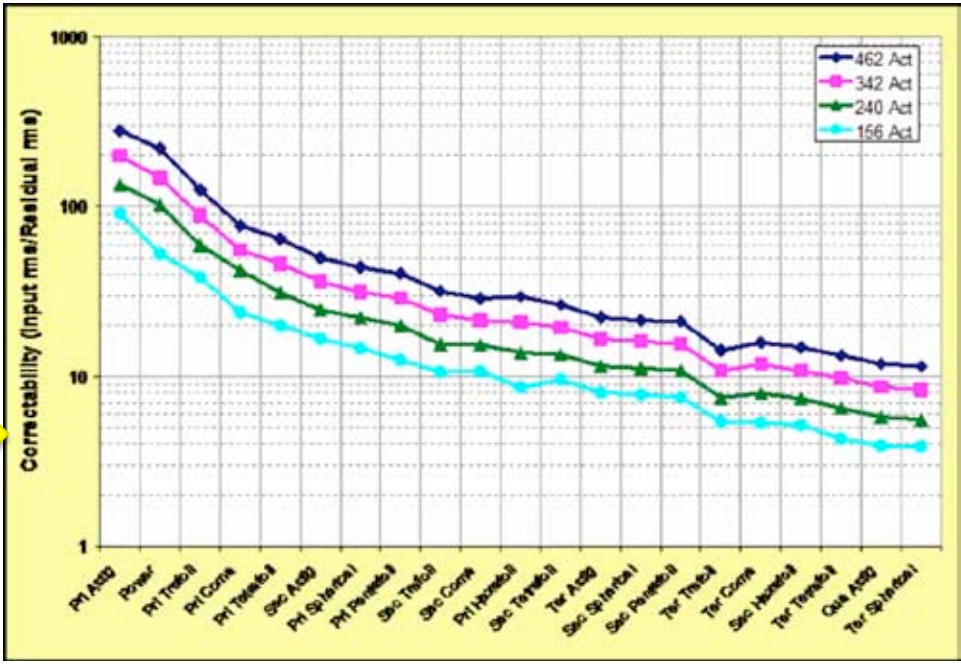
- Magnetrons create Ar+ plasma to drive atoms off the targets and onto the mandrel
- Switching between multiple targets creates multilayers
- Nanolaminate uniformity and strength assured by: ultra-stable processes
- Nanolaminate surface smoothness replicates mandrel

Substrate Design Considerations

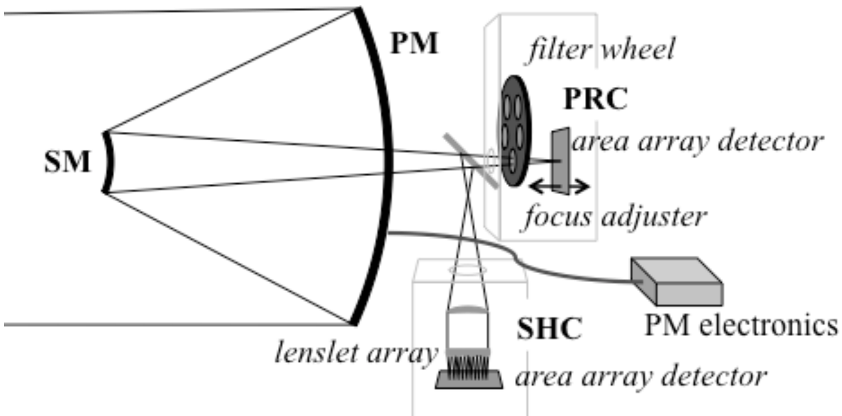


- **Substrate design must meet multiple objectives**
  - Optical performance is improved with more cells/actuators
    - At the expense of mass and complexity
    - Improved with multiple levels of ribs with differing heights
  - Stiffness: first mode >> 100 Hz
  - Mass: areal density typically 7-10 kg/m^2 for meter-class AHMs
  - CTE balanced by selection of actuator interface tabs

- **FEA models are built for candidate designs**
- **Structural/optical analyses are used to trade design objectives and constraints**
  - Correctability
  - Mass
  - Stiffness
  - Actuator tab material



Wavefront Sensing and Control

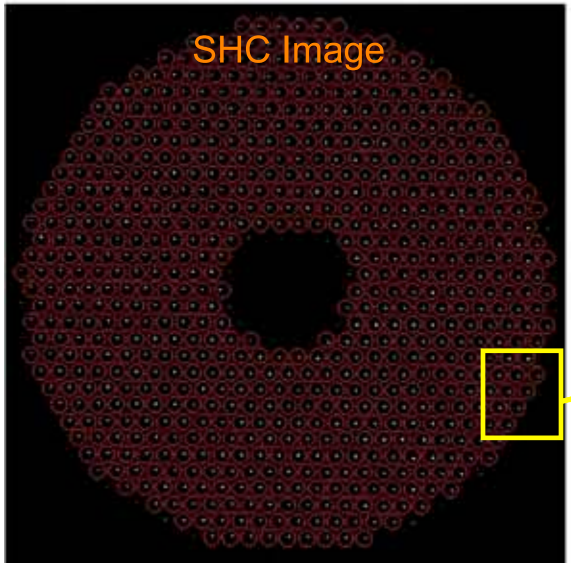


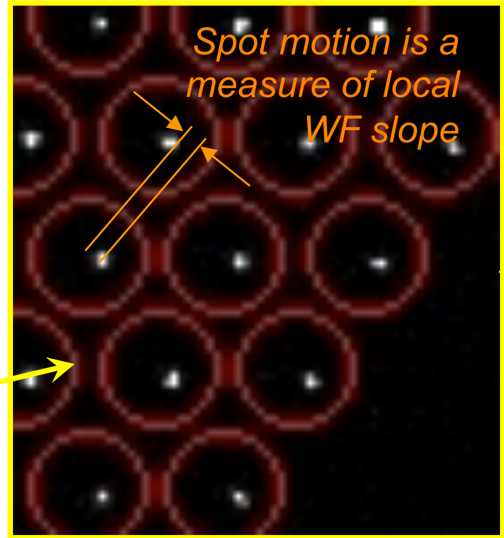
- **WFS&C Elements**
  - Imaging Camera ("PRC") with area array detector and narrow-band filter
  - Focus adjust mechanism
  - PM actuator electronics
  - Shack-Hartmann Camera ("SHC"), with area array detector, pupil imaging lens and lenslet array

- **WFS&C Operations are performed while observing a star**
  - *Initialization WFS&C* uses SHC for large WF capture range (> 30 λ), and PRC for high resolution and high accuracy
    - Use of PRC Imaging Camera measures WF in the main science camera – no non-common path
    - Run once at the beginning of the mission
  - *Maintenance WFS&C* uses PRC only, with minimal/no impact on science ops
    - Keeps WFE within spec
    - Run periodically throughout the mission (1/day to 1/week rate)

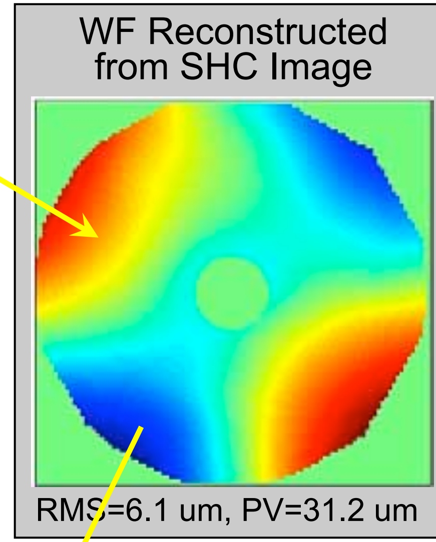
- **Image-based WF sensing using the PRC**
  - Modified Gerchberg-Saxton (MGS) phase retrieval software proven through operations on many platforms

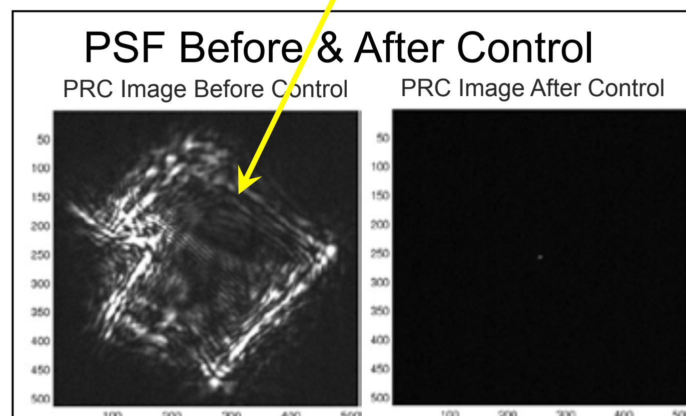
SHC Large Capture Example





– Data taken using white light source and open filter

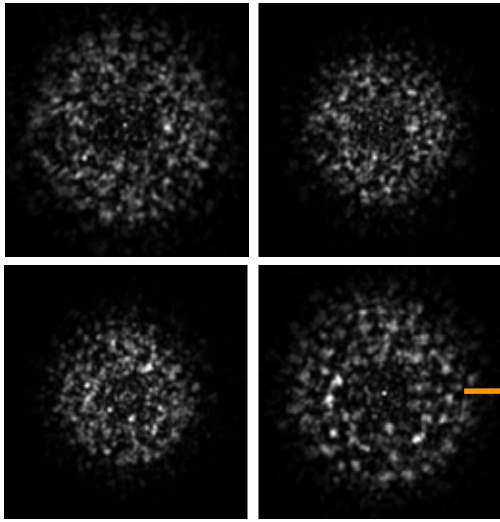




- ***WFS&C Experiment*** **used an AHM, portable SHC and PRC, and autocollimating flat**
- **SHC results show large capture range WF control**
  - Initial SHC WF error was 31 um (P-V), 6 um (RMS), double-pass
- **After SHC control, WF error was 80 nm RMS in the SHC, 116 nm in the PRC**

PRC Fine Control Example

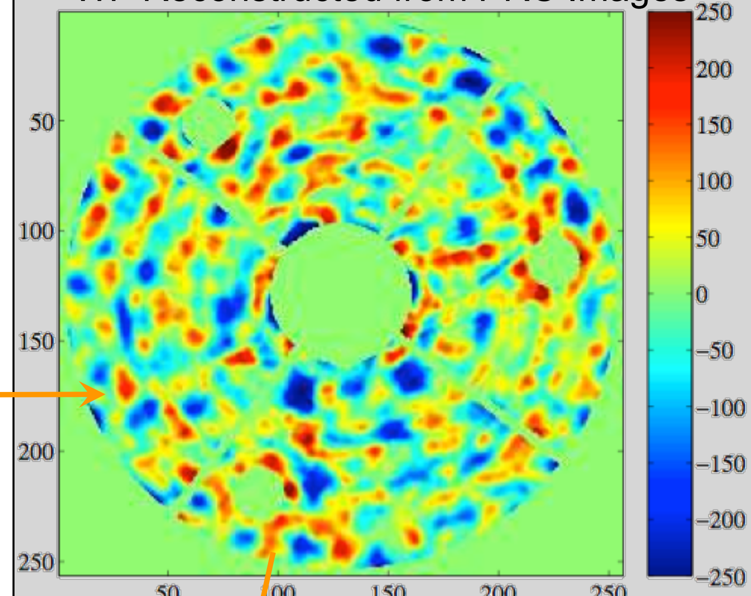
Defocussed PRC Images



- *Data taken using white light source*
- *Narrow-band Filter*

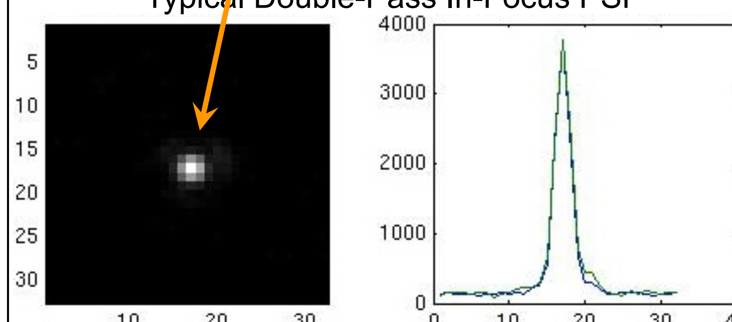
Control used 18% of capacity, 9 V on average

WF Reconstructed from PRC Images



Double-pass WFE = 83 nm (RMS)
Equivalent single-pass WFE = 42 nm (RMS)

Typical Double-Pass In-Focus PSF



- ***WFS&C Experiment* continues using the PRC imaging camera for *image-based WF sensing***
- **One or more iterations of control to achieve diffraction-limited WFE**
- **Performance is confirmed by the high-quality “single-pixel” in-focus PSF**