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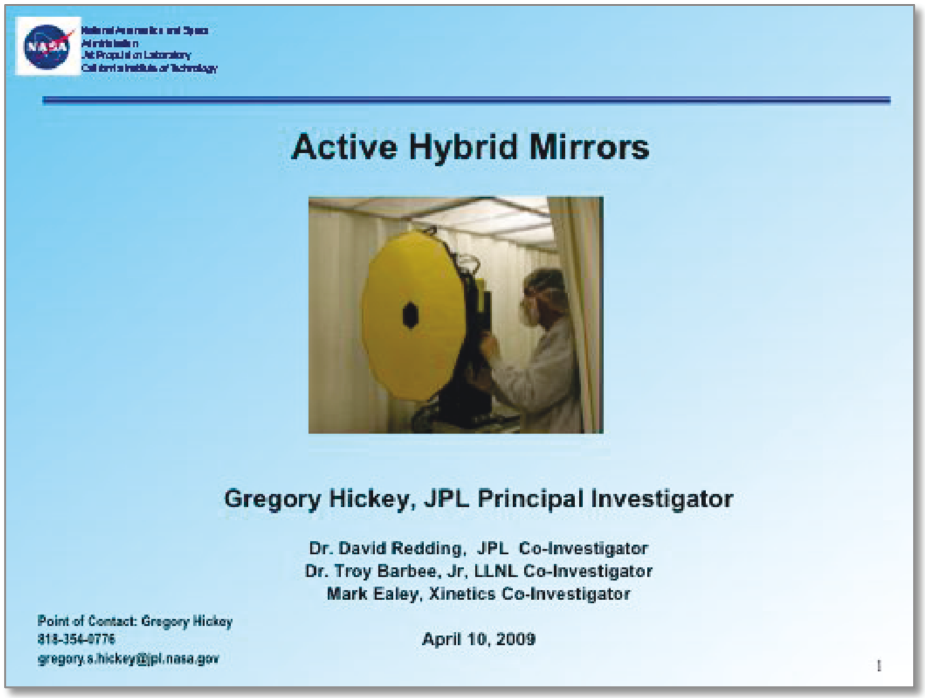
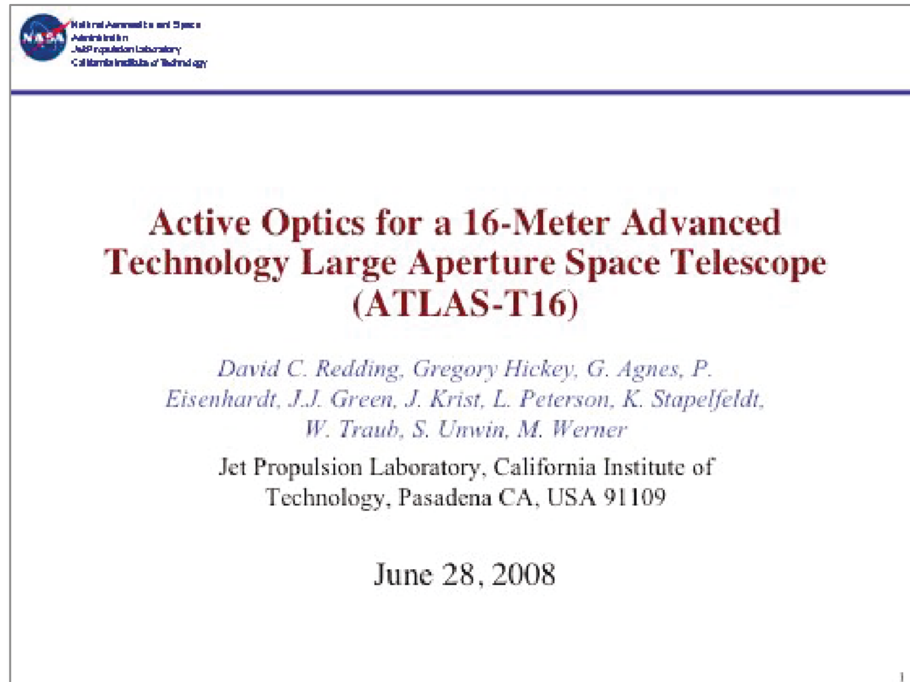
Active Optics and Wavefront Control



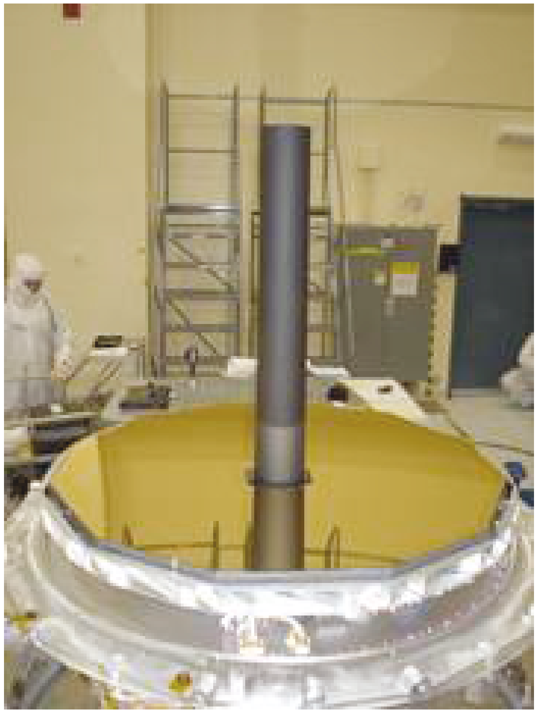


David Redding

Active Hybrid Mirrors (AHM)

- **Active Hybrid Mirrors (AHM) is this new paradigm for making affordable meter class large optics**
  - A combination of precision replication and active control

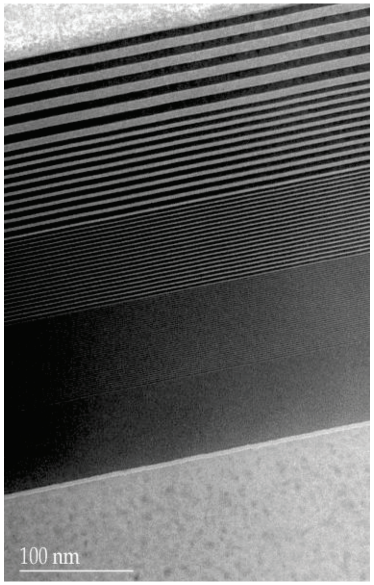
- **AHM's are the combination of three distinct technologies**
  - Facesheet: Nanolaminate foil (LLNL)
  - Substrate/Figure Control: Precision actuation integrated in silicon carbide (NG/ Xinetics, Inc)
  - Wave Front Sensing and Control:Phase Retrieval Camera and WFC algorithms (JPL)



AHM Hybrid Mirrors

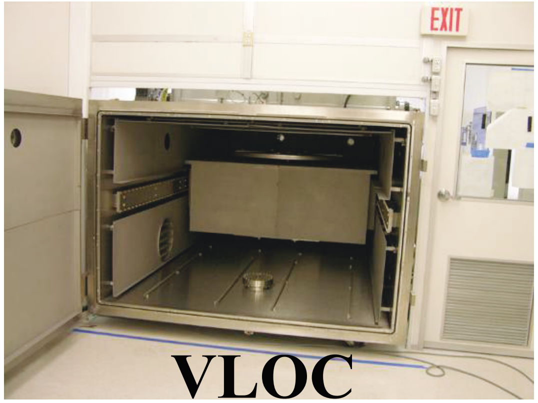
Precision Replicated Nanolaminate Mirrors

- **Nanolaminates Material Development**
  - Nanolaminate materials are multi-layer metallic foils grown by sputter deposition with atomic-scale control
  - Very thin, lightweight, flexible but stiff structures with low scatter, optically precise surface finish
  - Current material systems have tailorable low thermal expansion and low residual thermal stress to match AHM SiC substrates thermal expansion
  - Fabrication time is independent of diameter, typically 3 to 4 days dependent on thickness



TEM cross section of a ZrC/Si nanolaminate

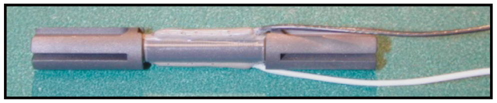
- **Current Nanolaminate Mirror Production Capability at LLNL**
  - 1.2 m Very Large Optical Coating (VLOC) nanolaminate processing facility
    - Four 1.4 m long magnetron sputtering guns
    - Mandrel table linear motion and rotation computer controlled to provide uniform deposition
  - Precision Cleaning Facility capable of cleaning 1.5 m master mandrels to semiconductor cleanliness levels



Advanced Silicon Carbide Substrates

- **AHM utilizes state of the art silicon carbide for advanced structures and elecrostrictive actuators**
  - Nano-structured silicon carbide structures that are ultra-lightweight, have exceptional dimensional stability and consistent high structural properties
  - High Stability PMN electrostrictive actuators that provide nanometer level of control authority
  - Robotic bonding of Hybrid Mirrors that ensure high quality, reproducible bonding processes that are scalable to meter class optics

85 cm Silicon Carbide Substrates



Ultra Stable PMN Actuators

Robotic Bonding

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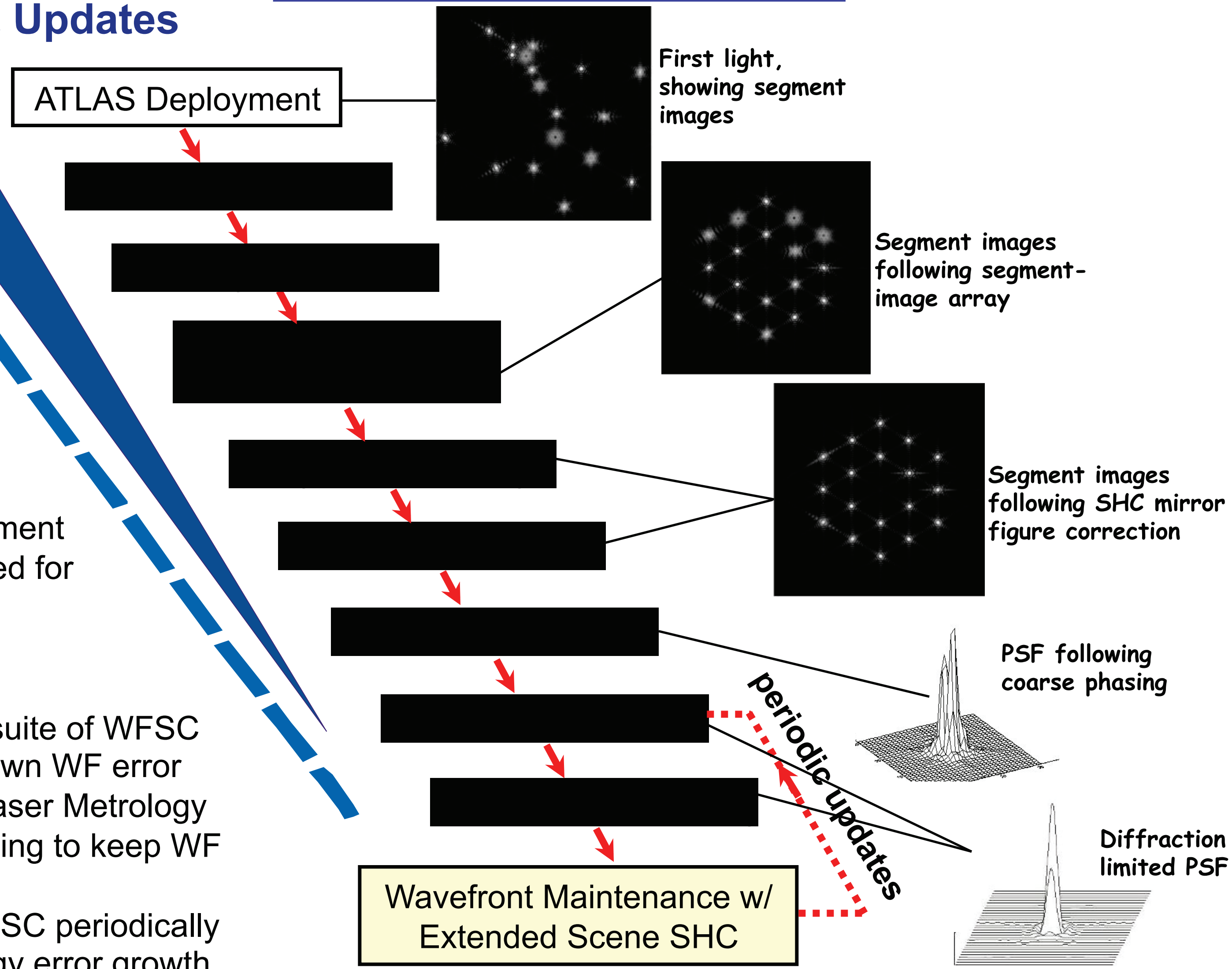
WF Sensing and Control

Chart borrowed from JWST – Scott Acton/Ball

WF Initialization & Updates



WF Maintenance

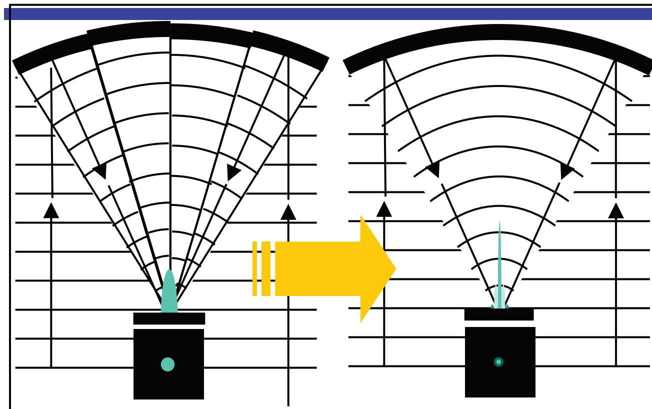
Challenges

- Large initial WF error after segment deployment
- Small final WF required for system performance

Solutions

- **Initialization**: Use a suite of WFSC algorithms to bring down WF error
- **Maintenance:** Use Laser Metrology and low-BW WF sensing to keep WF error in spec
- **Updates:** Repeat WFSC periodically to limit Laser Metrology error growth

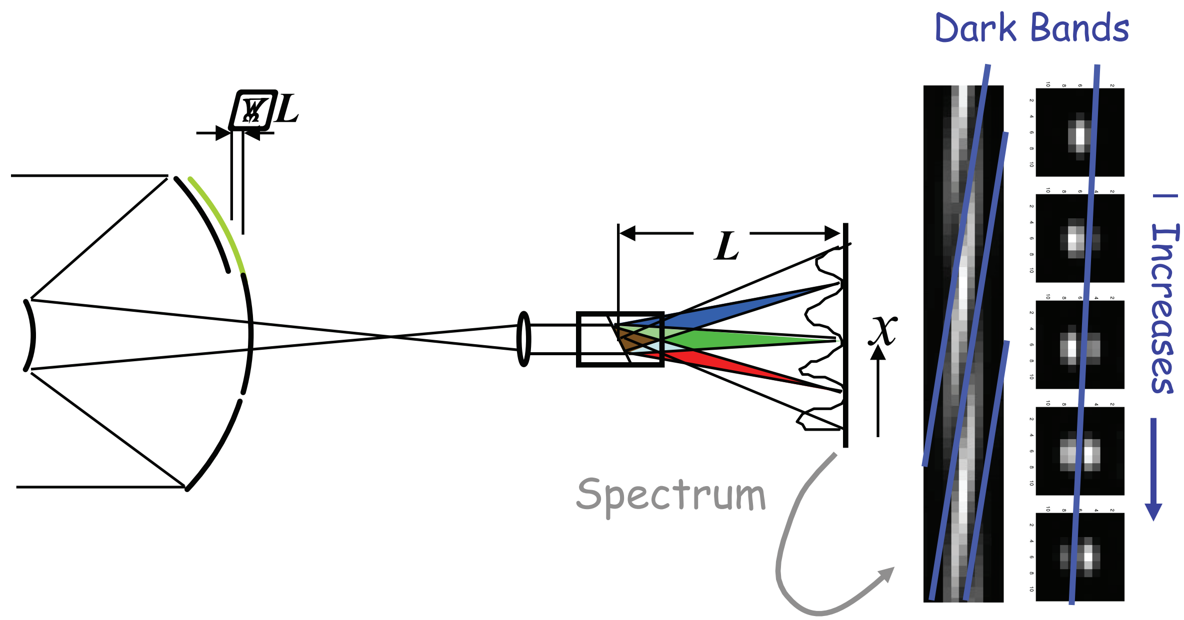
Coarse Phasing: Dispersed Fringe Sensing



Dispersed-Fringe Sensing enables the absolute phasing of the segments to within 1 wave

- **DFS uses segment steering to select segment combinations for control**
- **“Dispersed Hartmann Sensing” (DHS) is DFS with prisms that select edge patches only**
  - JWST approach

- **Dispersed-Fringe Sensing (DFS) uses a dispersive element (a grism) in an imaging camera to spread spot images into linear spectra**



- **Wavelength variation along the spectrum modulates fixed path differences between segments to create interference fringes:**
  - Bright peak where l is coherent with *dL*
  - Dark null where l is out of phase with *dL*
- **Period of fringe gives absolute piston displacement**
- **Slope of dark bands gives the sign**

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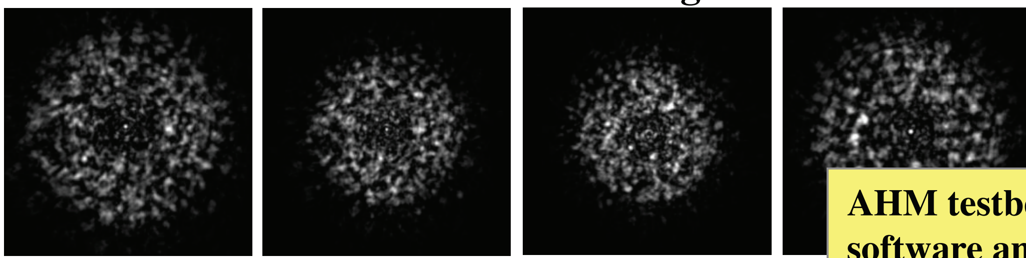
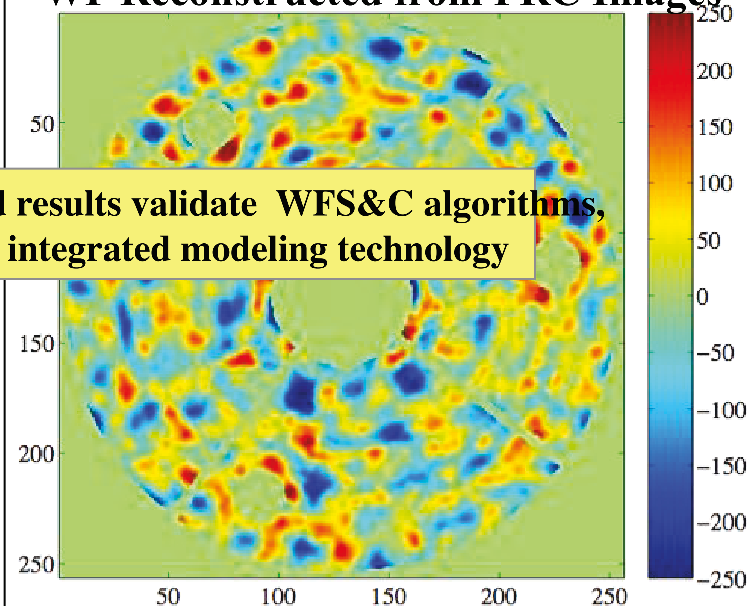
Wavefront Sensing and Control

Defocussed PRC Images



WF Reconstructed from PRC Images

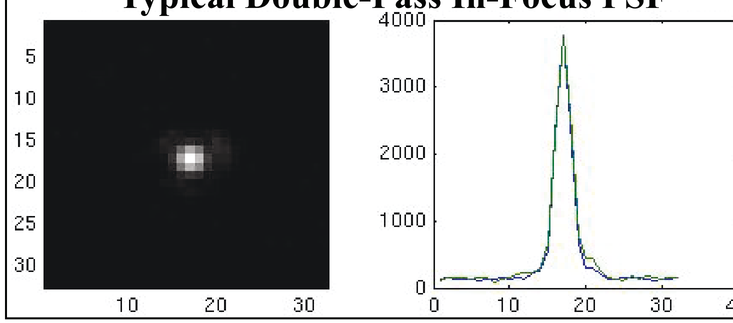


Double-pass WF = 83 nm (RMS)
Equivalent single-pass WFE = 42 nm (RMS)

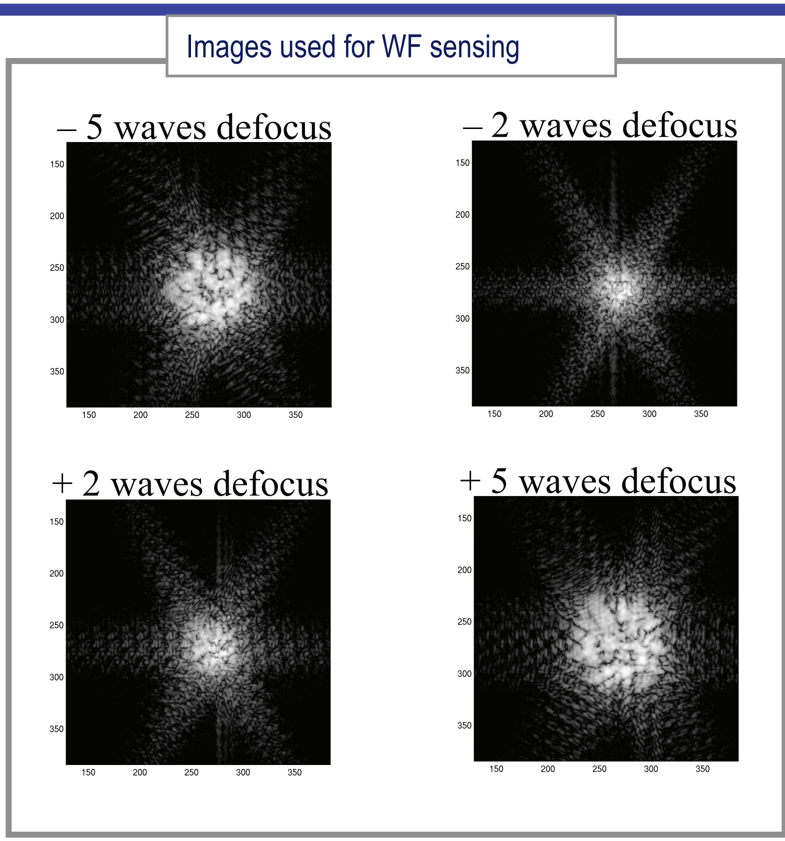
AHM testbed results validate WFS&C algorithms, software and integrated modeling technology

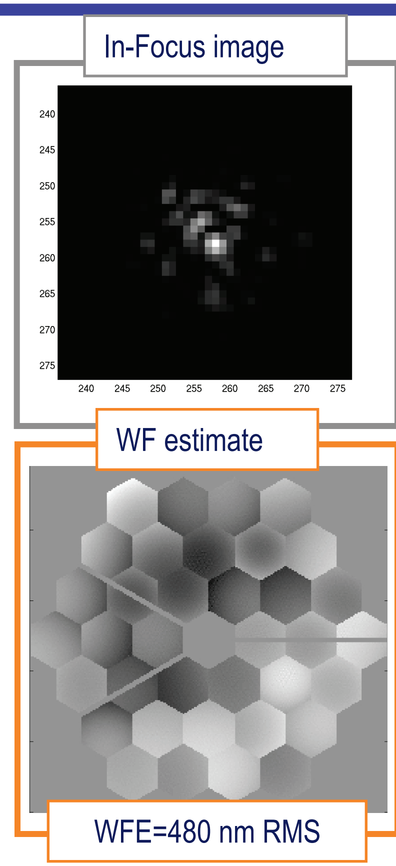
- **AHM uses WFS&C technologies developed by JPL for NASA and other agencies**
  - Applied on JWST/NGST testbeds and pathfinder optics, Spitzer/SIRTF, TPF/High Contrast Imaging Testbed, Palomar Observatory Hale Telescope, and many others
- **Proven JPL technologies also support follow-on segmented mirror telescopes**
  - Segmented Mirror WF Control
  - Shack-Hartmann WF Sensing
  - Phase Retrieval WF Sensing
  - Precision Metrology
  - Integrated Modeling

Typical Double-Pass In-Focus PSF

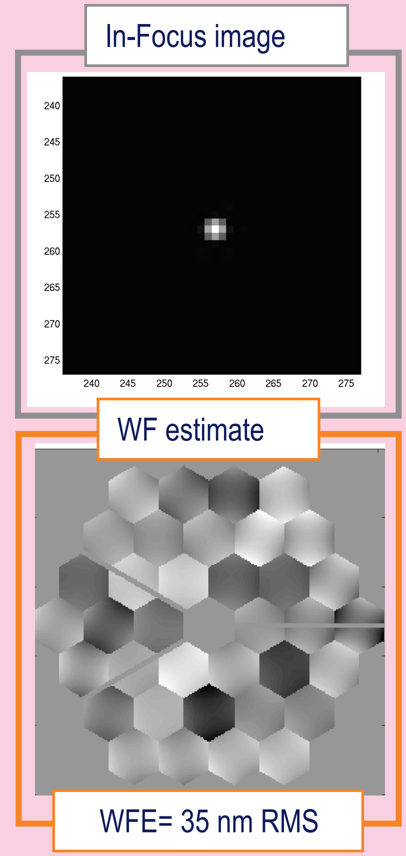


Example: Fine-Phasing 36-Hex PM





- Post-control WF meets 150 nm objective



- Fine Phasing uses MGS Phase Retrieval to estimate WF
- WF control is applied using segment RB and RoC actuators

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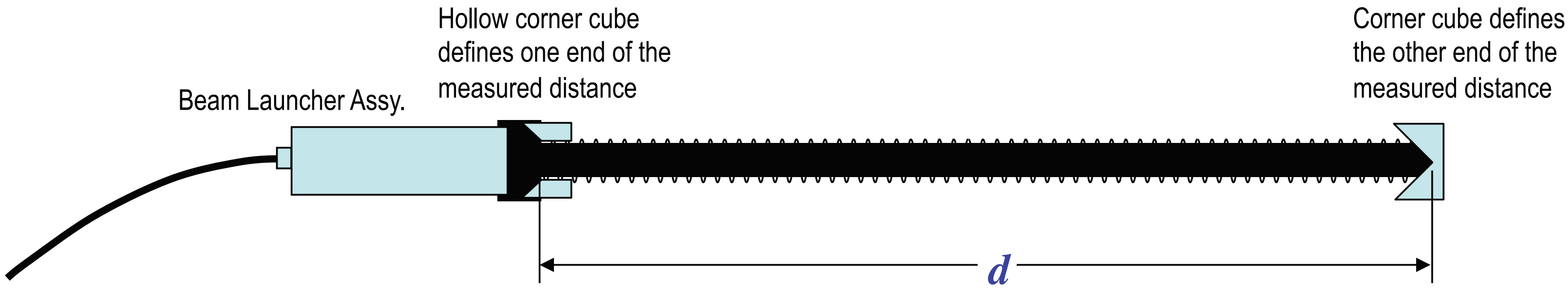
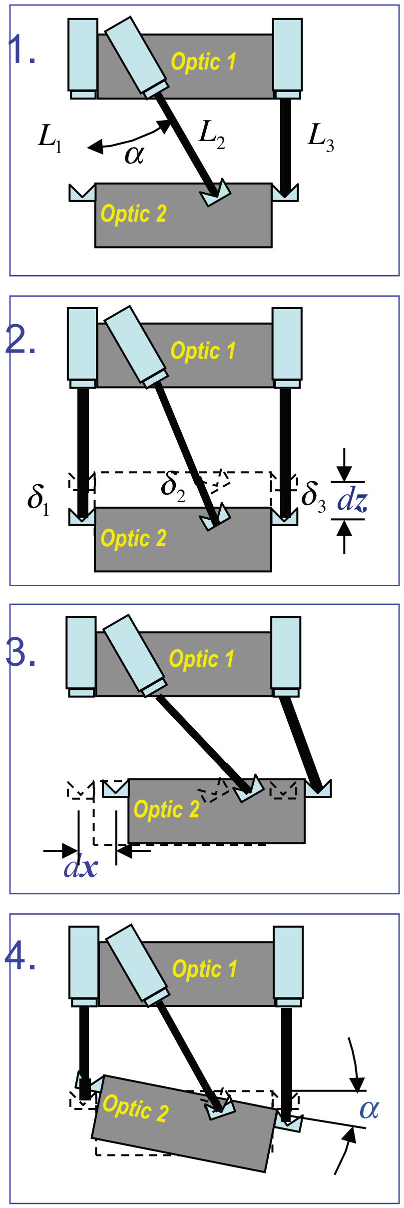
A Laser Distance Gauge



- **At the conceptual level, a Laser Distance Gauge (LDG) is a "yardstick," with "inchmarks" provided by the interference fringes of the laser beam**
  - Changes in the distance ***d*** between the Beam Launcher (BL) and the Corner Cube (CC) are measured as phase shifts between input and output beams
    - Intrinsic accuracy is better than 1 nm
    - We "count fringes" to track large changes in ***d***
    - A 2-color mode provides a large "absolute mode"
- **We can keep the BL and CC the same distance apart, by position feedback control of the BL and/or CC to keep *d* constant**
  - LDG runs at high BW (nominally 1 kHz)

- **A SIM Mission-derived technology application funded by JPL R&TD**

A 2-Dimensional LT Example



- **This 2-D example illustrates use of LDG measurements to estimate rotational as well as translational DOFs between bodies**
  1. Nominal geometry. There are 3 relative DOFs – $\boldsymbol{x}$ and $\boldsymbol{z}$ translation, and θ rotation
  2. Changes in LDG measurements due to a $\boldsymbol{z}$ translation:

     $\delta_1 = dz; \qquad \delta_2 = \cos(\alpha)dz; \qquad \delta_3 = dz;$
  3. Changes in LDG measurements due to an $\boldsymbol{x}$ translation:

     $\delta_1 = 0; \qquad \delta_2 = \sin(\alpha)dx; \qquad \delta_3 = 0;$
  4. Changes in LDG measurements due to a θ rotation:

     $\delta_1 = r_1\theta; \qquad \delta_2 = r_2\sin(\alpha)\theta; \qquad \delta_3 = r_3\theta;$

- **The measurement in matrix form**

$$\delta = \begin{bmatrix} \delta_1 \\ \delta_2 \\ \delta_3 \end{bmatrix} = \begin{bmatrix} 0 & 1 & r_1 \\ \sin(\alpha) & \cos(\alpha) & r_2\sin(\alpha) \\ 0 & 1 & r_3 \end{bmatrix} \begin{bmatrix} dx \\ dz \\ \theta \end{bmatrix} = Cx$$

- **A simple state estimator**

$$x = C^{-1}\delta$$

- **Feedback control based on the δ measurements can keep the truss aligned**

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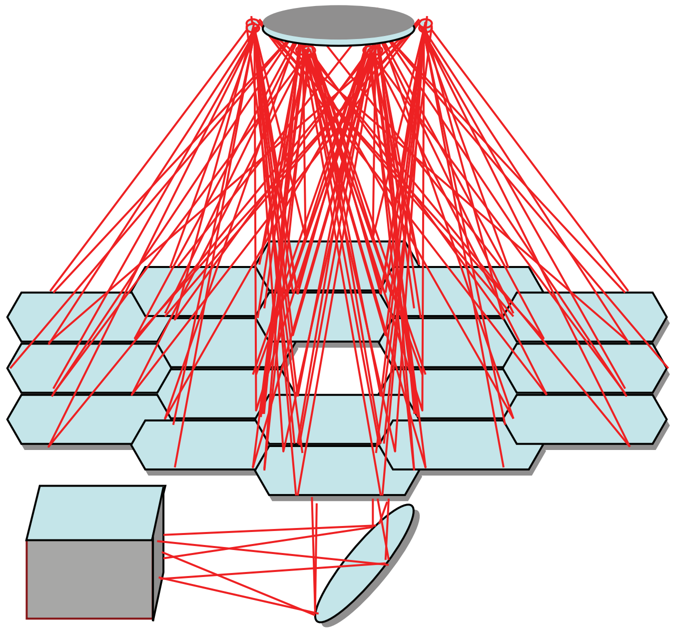
The Full 3-Dimensional Laser Truss



- **The same approach is extended for the full 3-D LT**
  - 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