National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Large Space Apertures: Kick-off Workshop

State of the Art: Active and Adaptive Optics

David Redding

November 10, 2008

Acknowledgement

- **This paper was first presented at the 2008 SPIE Astronomical Instruments Symposium, Marseille, France:**

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Active Optics for a 16-Meter Advanced Technology Large Aperture Space Telescope (ATLAS-T16)

David C. Redding, Gregory Hickey, G. Agnes, P. Eisenhardt, J.J. Green, J. Krist, L. Peterson, K. Stapelfeldt, W. Traub, S. Unwin, M. Werner

Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA, USA 91109

June 28, 2008

3

ATLAST Study Goal: ID Tech Needs

- **The Ares-V cargo launch vehicle offers the possibility of a truly large space telescope in the 2020 time-frame**
  - 8.8 m diameter by 18.7 m long shroud
  - 55,600 kg to L2 orbit

- **ATLAST Study objective is to create a technology plan leading to development of a new flagship mission for NASA**
  - Study team led by ST ScI (Marc Postman), with participation from 4 NASA Centers, 4 Universities, and 2 system contractors (Ball and NG)

- **Two concepts are being pursued:**
  - 16 m aperture, deployed telescope with a segmented Primary Mirror (PM)
  - 8 m aperture, monolithic, non-deployed telescope (H.P. Stahl, this meeting)

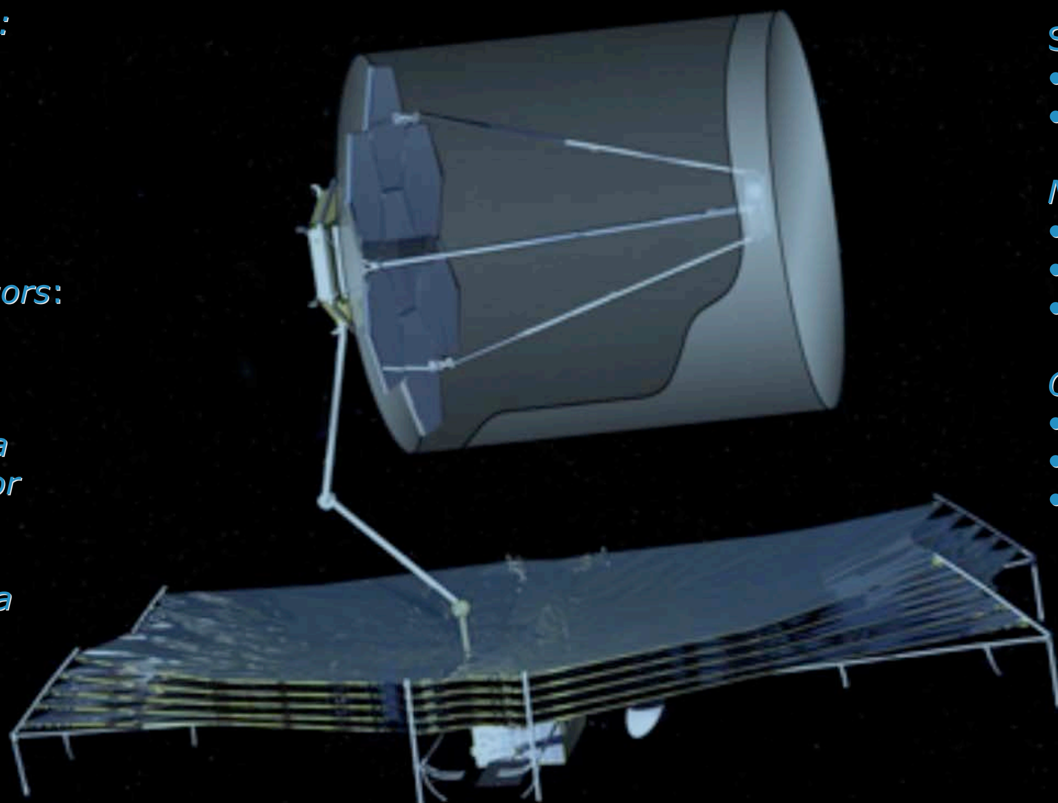
- **This paper considers the special technical challenges of the 16-m system**

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

WF Sensing and Control Baseline

Optics and optical controls:
- Segmented primary
  - *Deforming actuators*
  - *Rigid-Body actuators*
- Deployed secondary
  - *Rigid-Body actuators*

Instruments *and WF sensors*:
- High-dynamic range imager
- Visible imager
  - *Phase Retrieval Camera*
  - *Dispersed-Fringe Sensor*
- Spectrometer
- UV imager
- *Shack-Hartmann Camera*



Spacecraft System:
- Attitude Control
- Command and telemetry

Metrology System:
- *Laser Truss*
- *Edge sensors?*
- *IRU*

On-board processor:
- *Optical State Estimator*
- *WF Controller*
- *Pointing Controller*

- **Wavefront Sensing uses Imaging and Shack-Hartmann cameras and Laser Metrology to measure WF errors**
- **Wavefront Control uses the deformable/moveable PM segments to keep WF error small for diffraction limited image quality**
- **Line-of-Sight Pointing Sensing and Control will use a Fast Steering Mirror driven from Metrology and/or Guide Star error signals to limit jitter**

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

ROM Wavefront Control Requirements

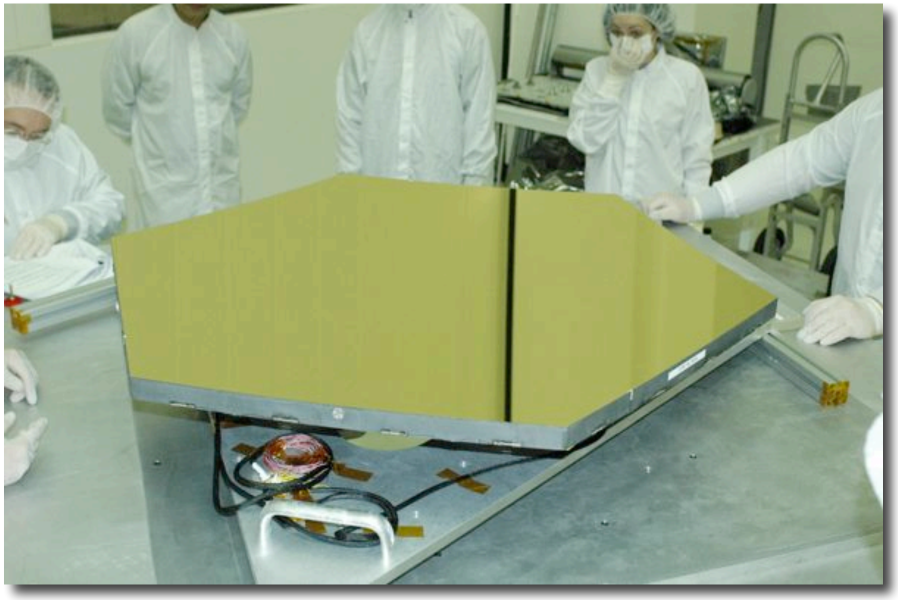
- **Exoplanet imaging is perhaps the most demanding task for an ATLAS-T16 telescope**
- **WF performance required will depend on implementation**
  – Does the Planet Imaging (PI) instrument provide a second layer of control?
  – Is an external occulter to to be used?

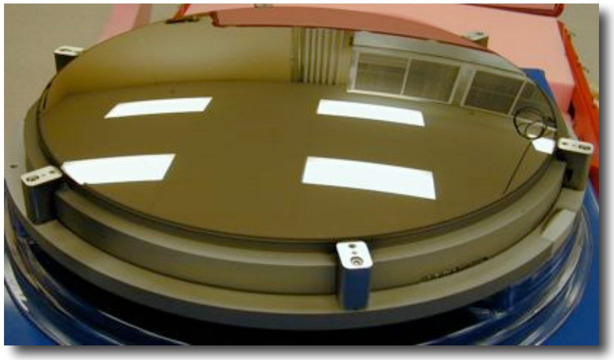
	No PF instrument	No WFC in PF instrument	Second stage of WFC in PI instrument	High BW WFC in PI instrument	External occulter	External occulter + moderate coronagrap
WF Error	10-40 nm	<1 nm	10-40 nm	10-40 nm	10-40 nm	10-40 nm
WF Stability	5-20 nm	<1 nm	<1 nm	5-20 nm	5-20 nm	1 nm

- **LOS pointing performance for PI is similarly extreme**

- **Target telescope WF performance for good general astrophysics performance**
  – Use a PI instrument with active WFC, or with an external occulter
    - Telescope static WFE < 10-40 nm RMS
    - Telescope WFE stability < 5-20 nm RMS

Lightweight Active Optics





- ATLAST-16 will require lightweight, actively controlled optics such as Active Hybrid Mirrors (AHMs)
- AHMs combine a cast SiC substrate with integrated ceramic actuators, with a Nanolaminate facesheet
- Nanolaminate facesheet is a multi-layer metallic foil grown by sputter deposition on a precision mandrel
- AHMs are fabricated by replication for minimum cost and manufacturing time
- AHM technologies are a joint development of NG Xinetics, LLNL and JPL

WF Control and Metrology Baseline

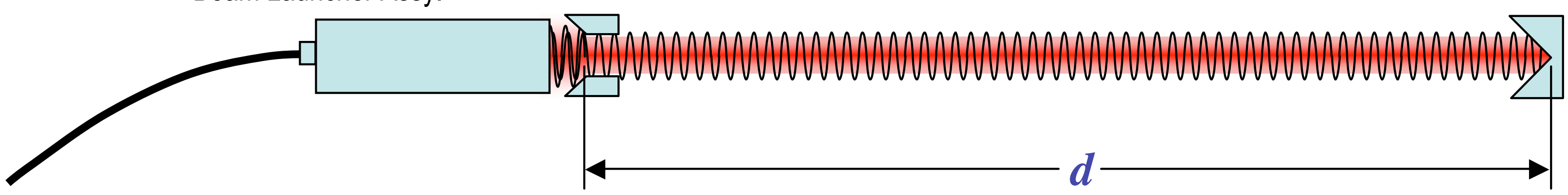
- **Initial WF Sensing and Control establishes the metrology set-point**
  - Star observations for WFS&C during commissioning, and 1/day after that
    - Full-spectrum for segment phasing
    - Full field for Telescope alignment

- **Segment thermal control keeps segment figure constant**

- **Metrology keeps alignments constant, compensating for thermal deformation of the supporting structures**

- **Metrology technology options:**
  - Laser Truss *Provides full observability of Telescope alignment errors*
  - Edge / Gap Sensors
  - Full-time WF sensing

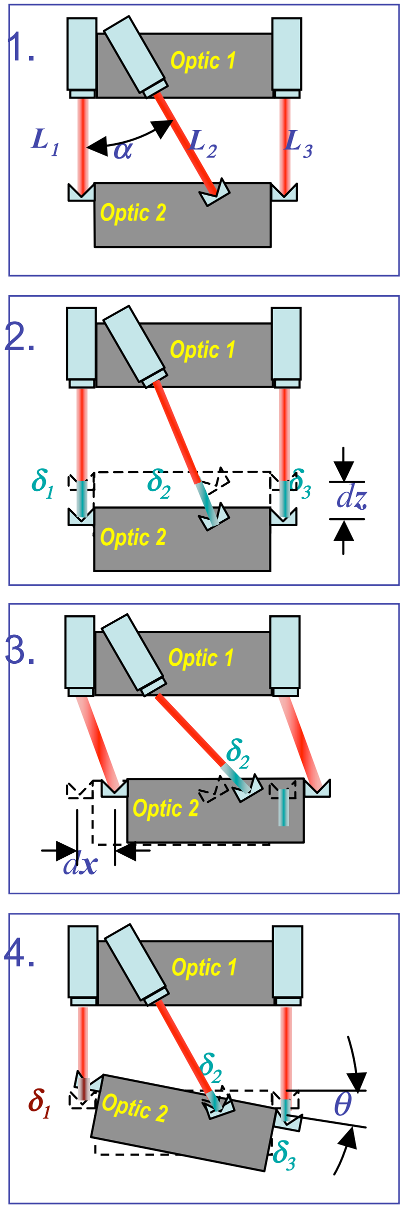
A Laser Distance Gauge



- **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 – ***x*** and ***z*** translation, and ***θ*** rotation
  2. Changes in LDG measurements due to a ***z*** translation:

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

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

     $\delta_1 = r_1\theta;\quad \delta_2 = r_2\sin(\alpha)\theta;\quad \delta_3 = r_3\theta;$
- **The measurement in matrix form**

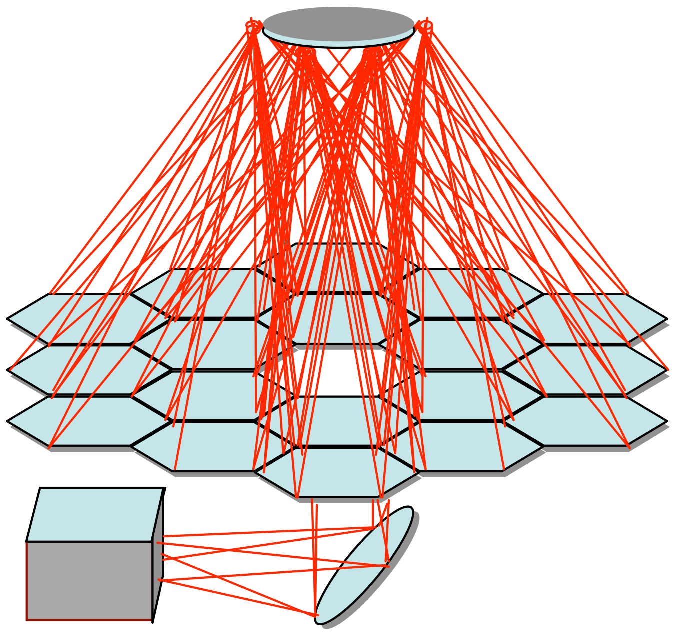
$$\delta = \begin{bmatrix}\delta_1\\ \delta_2\\ \delta_3\end{bmatrix} = \begin{bmatrix}0 & 1 & r_1\\ \sin(\alpha) & \cos(\alpha) & r_2\sin(\alpha)\\ 0 & 1 & r_3\end{bmatrix}\begin{bmatrix}dx\\ dz\\ \theta\end{bmatrix} = Cx$$

- **A simple state estimator**

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

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

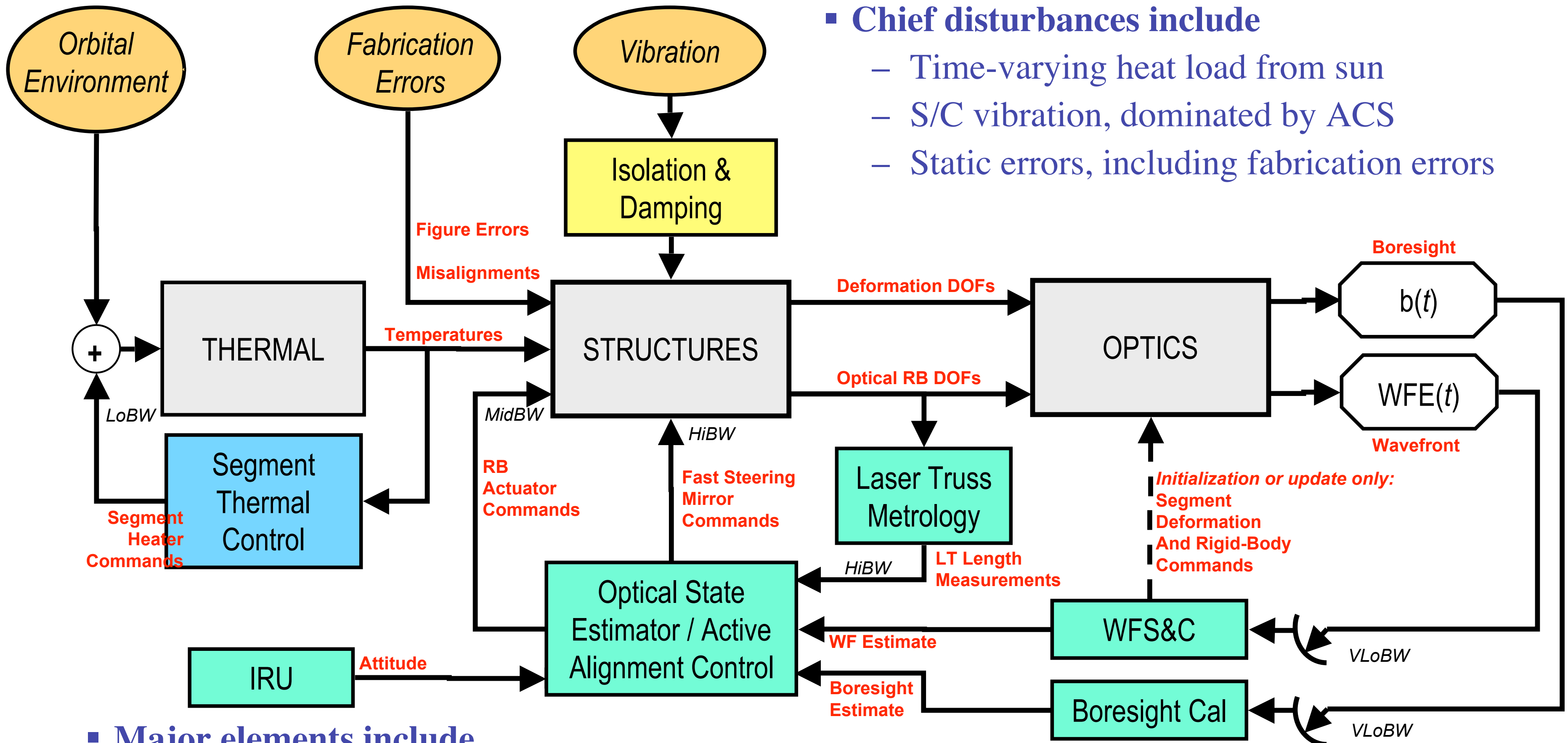
The Full 3-Dimensional Laser Truss



- **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

Block Diagram

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

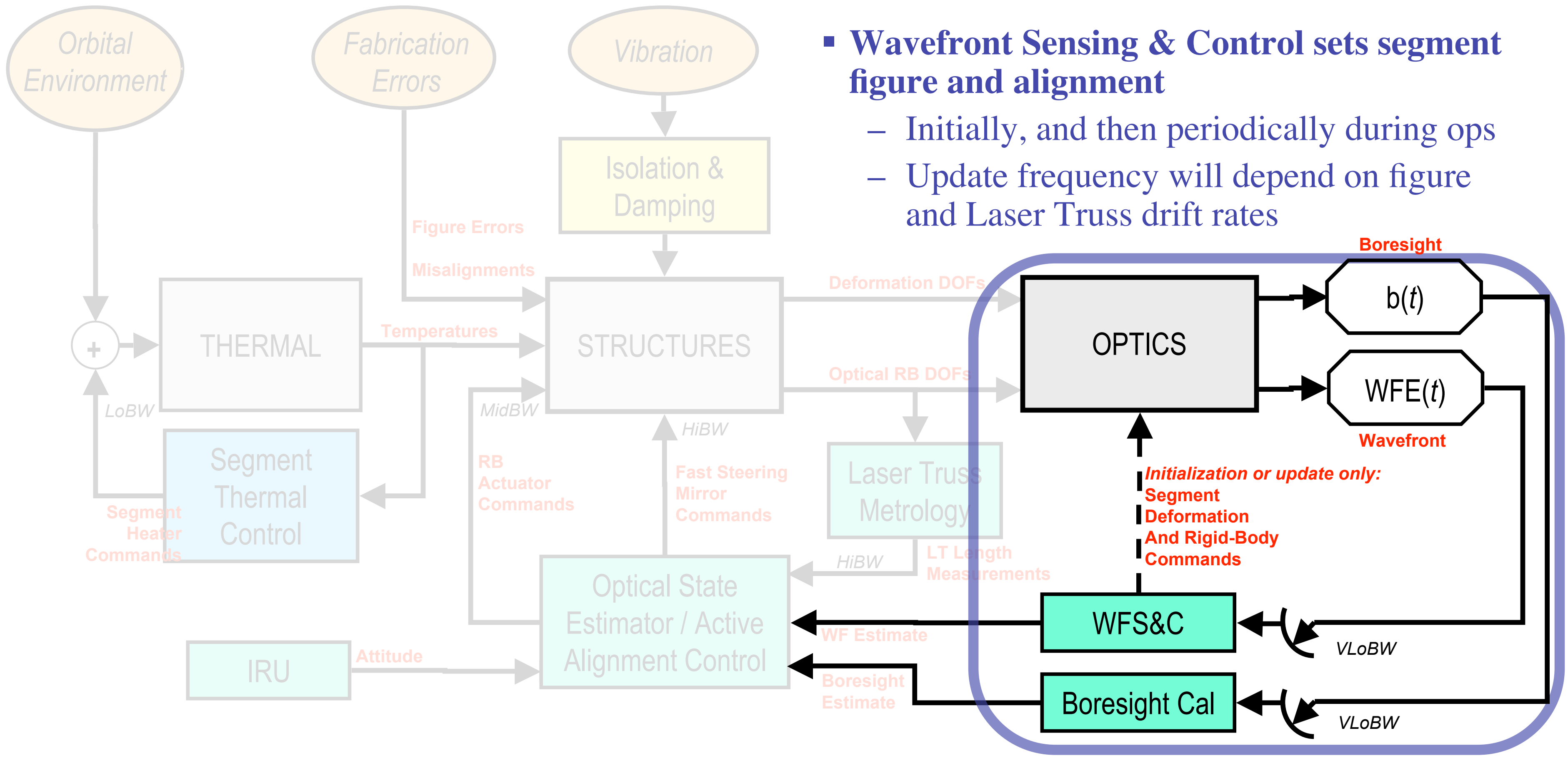


- **Major elements include**
  - Wavefront Sensing and Control
  - Laser Truss Active Alignment: active WF compensation and LOS pointing control
  - Segment Thermal Control to stabilize optical figure
  - Isolation and Damping to attenuate vibration disturbances

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Initial WFS&C

- **Wavefront Sensing & Control sets segment figure and alignment**
  - Initially, and then periodically during ops
  - Update frequency will depend on figure and Laser Truss drift rates

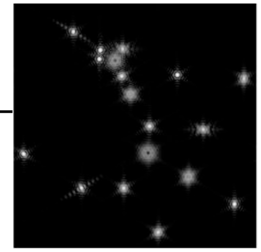


WF Sensing and Control

Chart borrowed from JWST – Scott Acton/Ball

WF Initialization & Updates

ATLAST Deployment

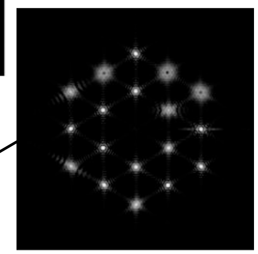


First light, showing segment images

SM Focus Sweep

Segment ID

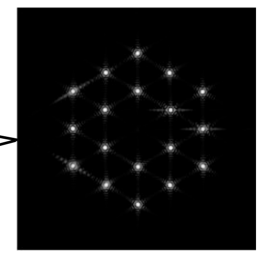
Segment Search (if needed)



Segment images following segment-image array

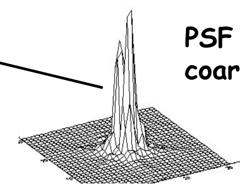
Segment Focusing

SHC Coarse Phasing



Segment images following SHC mirror figure correction

DFS Coarse Phasing



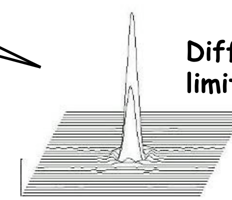
PSF following coarse phasing

PRC Fine Phasing

Multifield Fine Phasing

Wavefront Maintenance w/ Extended Scene SHC

periodic updates



Diffraction limited PSF

WF Maintenance

Challenges

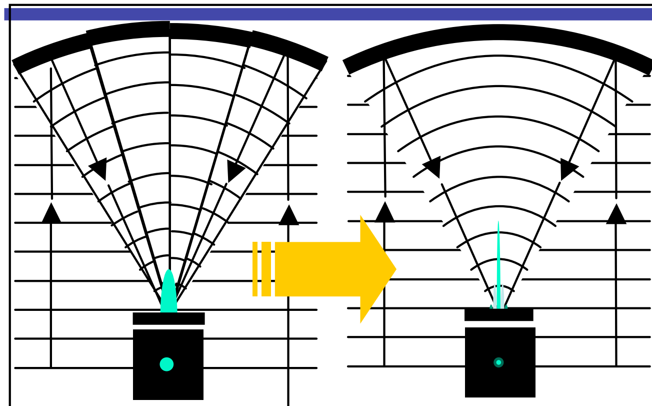
- Large initial WF error after segment deployment
- Small final WF required for system performance

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

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

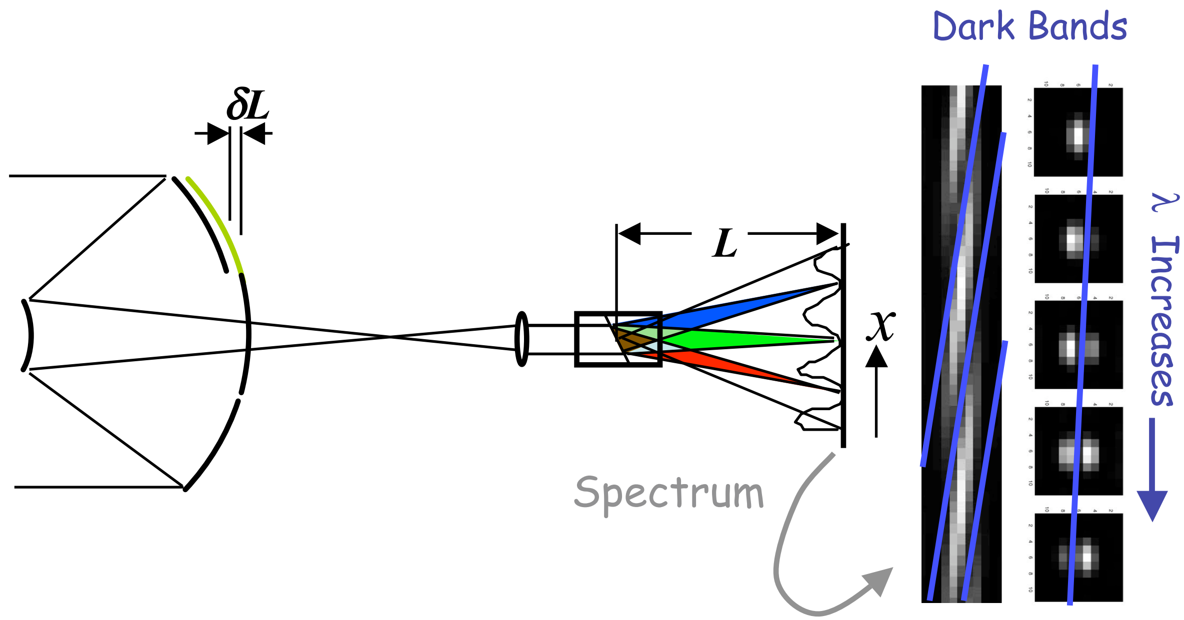
Coarse Phasing: Dispersed Fringe Sensing



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

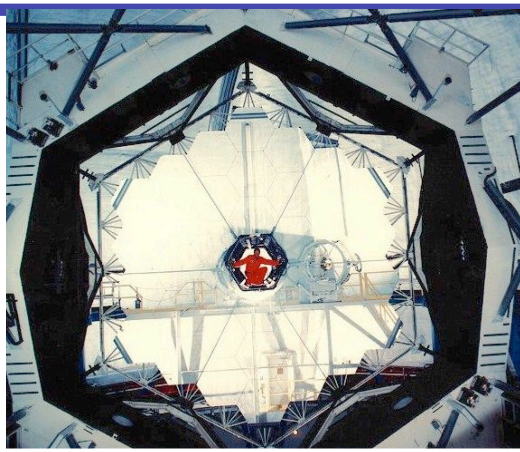
- **Dispersed-Fringe Sensing (DFS) uses a dispersive element (a grism) in an imaging camera to spread spot images into linear spectra**



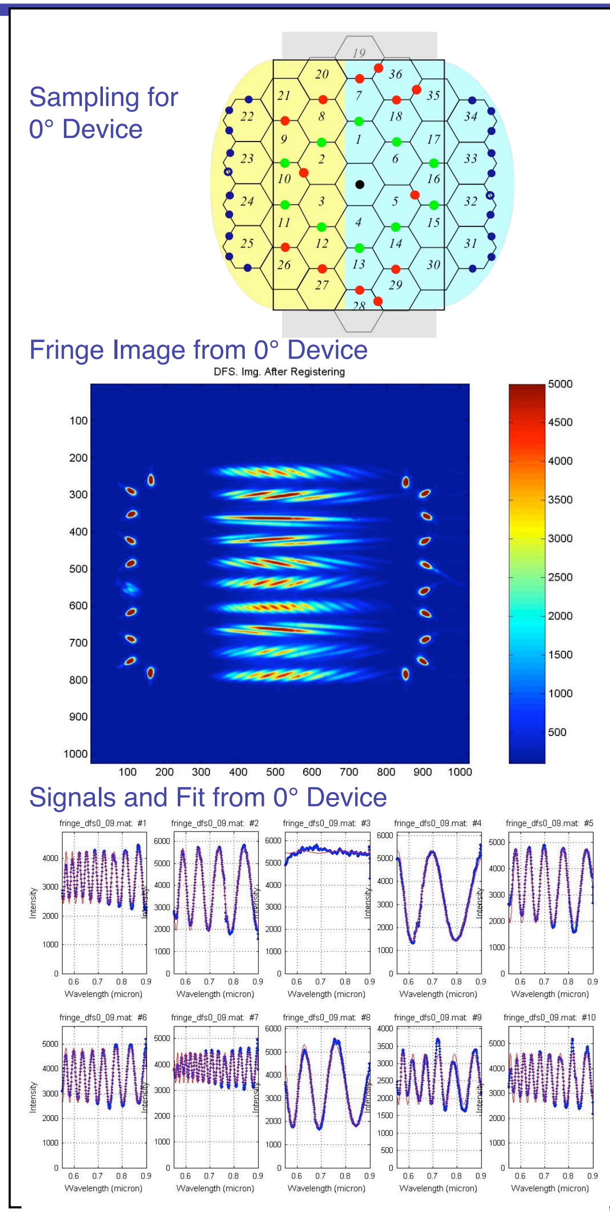
- **Wavelength variation along the spectrum modulates fixed path differences between segments to create interference fringes:**
  – Bright peak where λ is coherent with δL
  – Dark null where λ is out of phase with δL
- **Period of fringe gives absolute piston displacement**
- **Slope of dark bands gives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

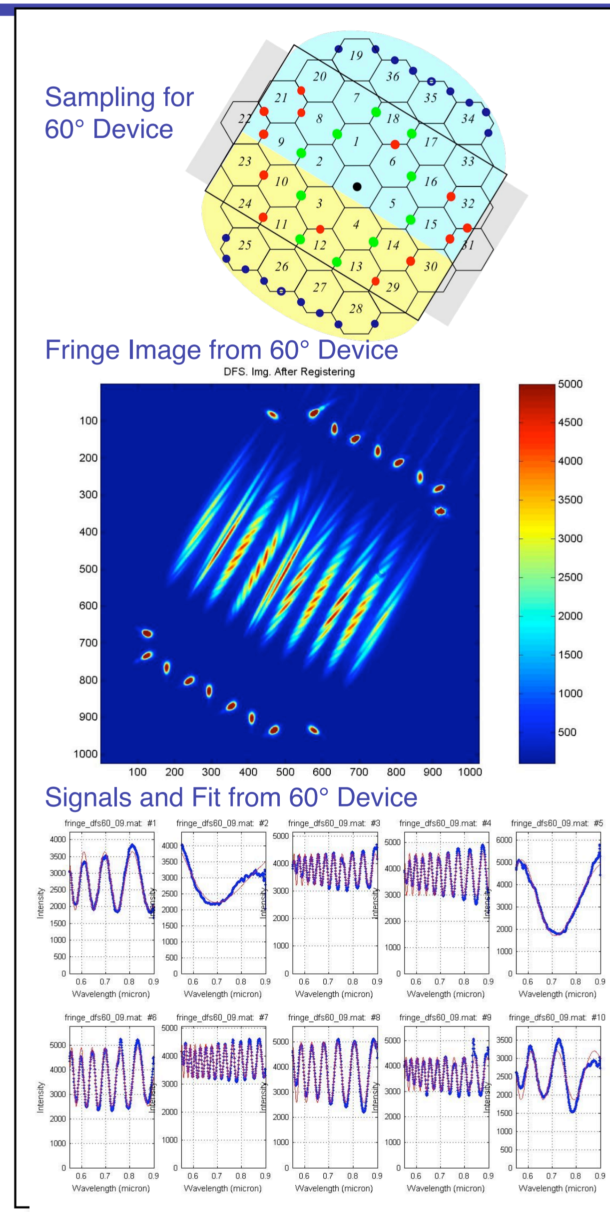
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Example: Keck DFS Experiment 2



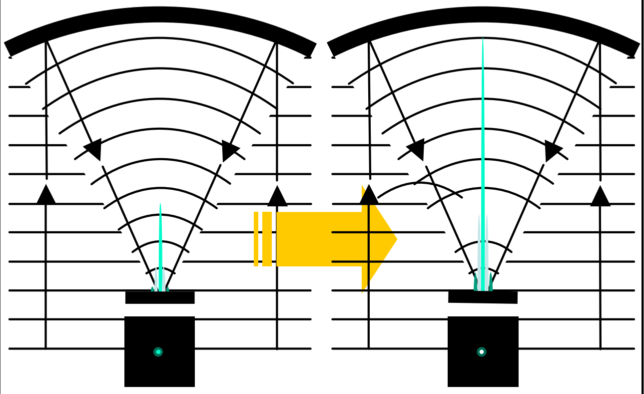
- **Two DHS devices were used in the second Keck experiment**
  - 0° and 60° grism orientations
  - 10 edges sampled in each image
- **Combination provides enough information to reconstruct piston of 18 segments**
  - Tilts constrained





National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

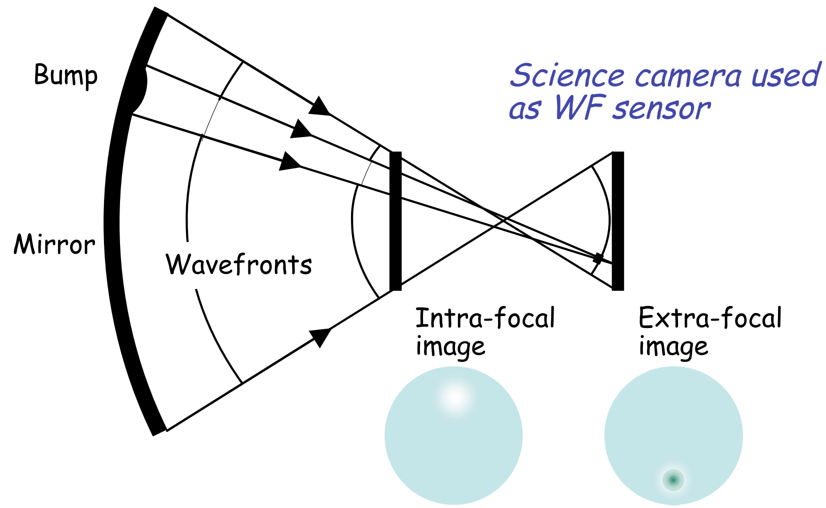
Phase Retrieval WFS



Phase Retrieval provides accurate, high-resolution WFS for commissioning and maintenance

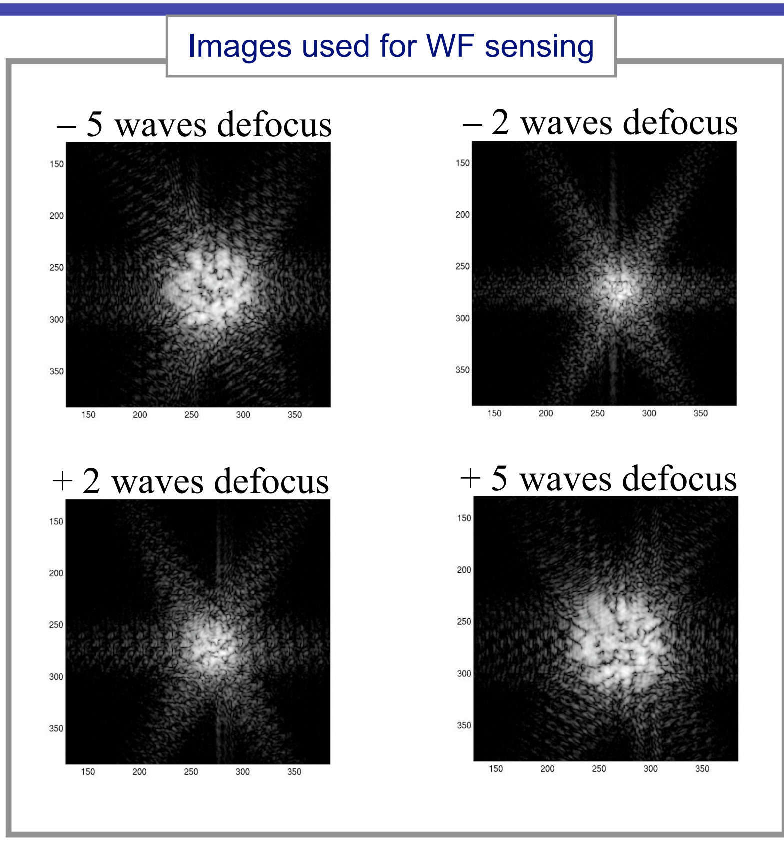
Updates figure of segments as well as optical alignments

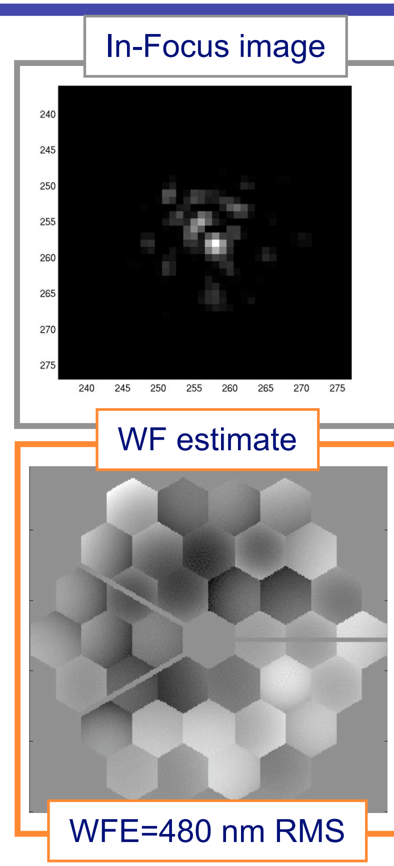
- **Image-based Phase Retrieval WFS offers**
  - High accuracy
  - High resolution
  - Can be performed in any camera, any field point
  - Minimum of non-common optics



- **Bumps on a mirror surface shift the focus of patches of the beam**
- **These show up as bright spots on one side of focus and dark spots on the other**
- **The pupil and defocussed images are related by Fourier transforms**
- **Iterative processing of multiple defocussed images correlates the intensity variations in each, derives common WF phase map**

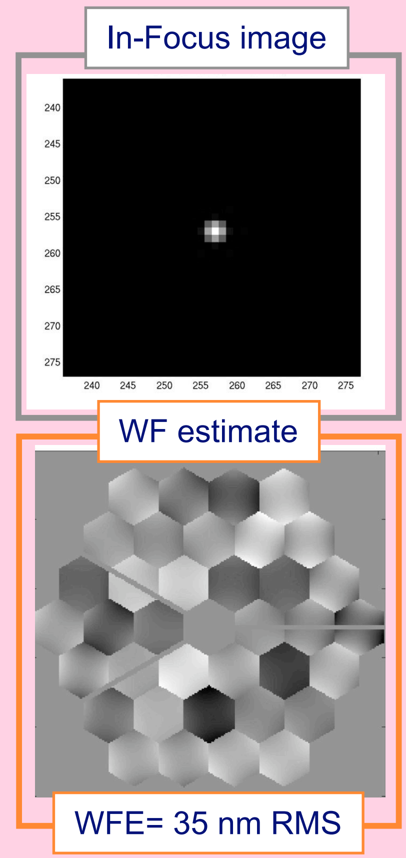
Example: Fine-Phasing 36-Hex PM





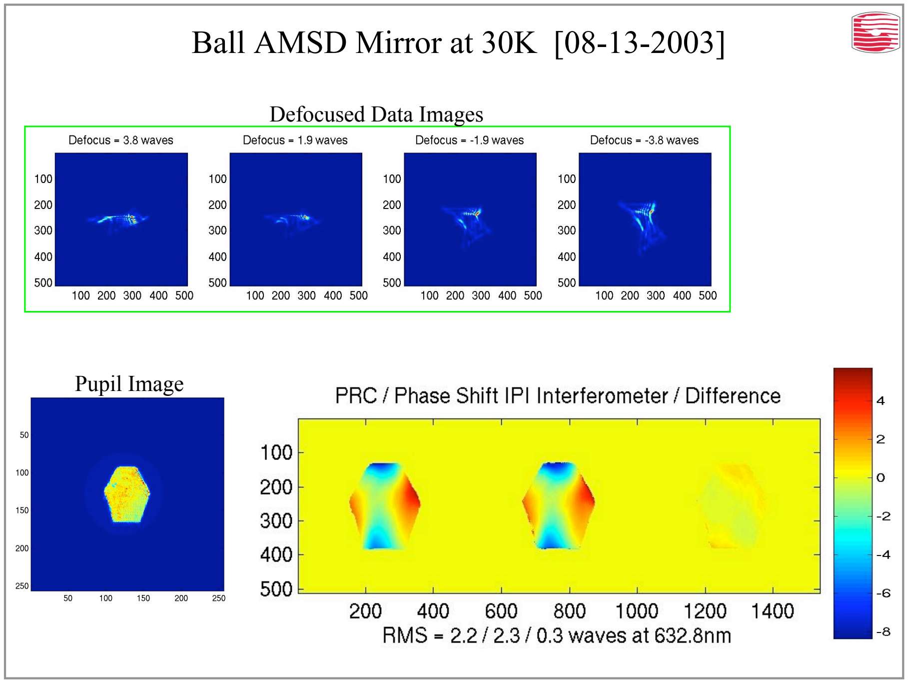
- Fine Phasing uses MGS Phase Retrieval to estimate WF
- WF control is applied using segment RB and RoC actuators

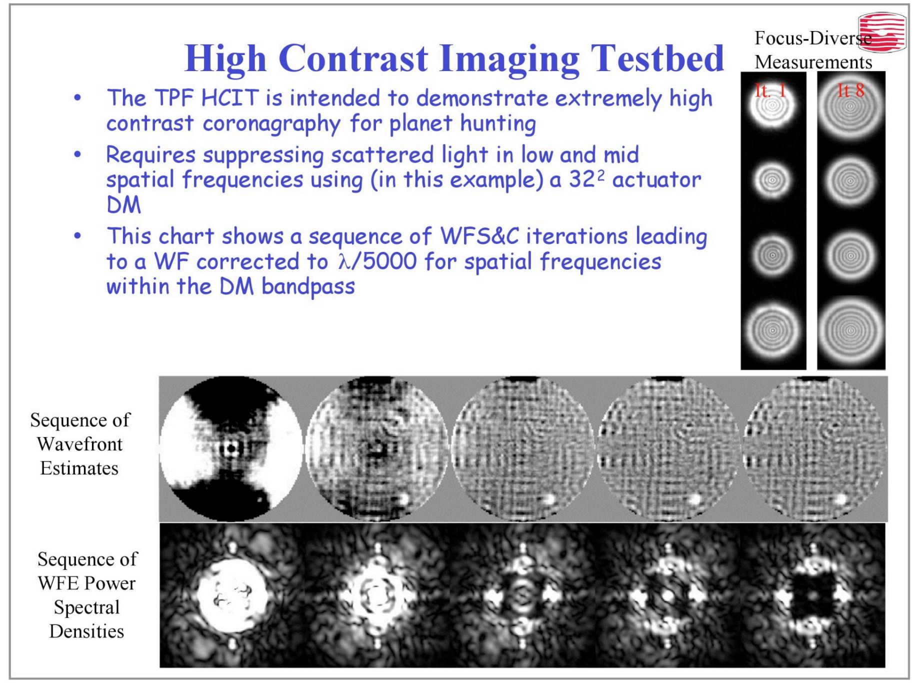
- Post-control WF meets 150 nm objective



National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

WFS Capture Range and Accuracy



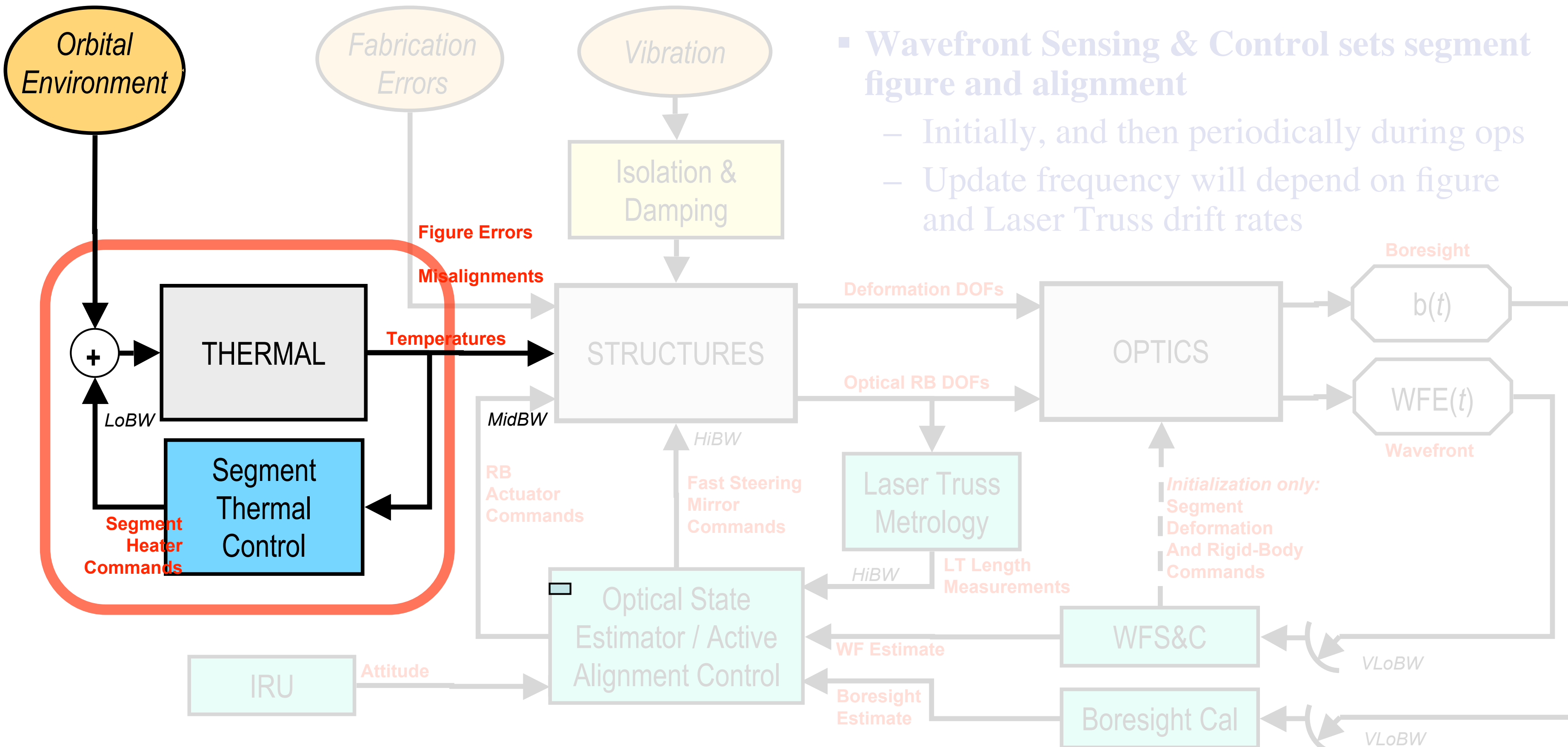


- **PRC was used to test the 1.3 m-class Advanced Mirror System Demonstrator (AMSD) beryllium mirror, built by Ball Aerospace snd tested at the MSFC XRCF facility**
- **Demonstrated >12 waves capture range, with < 8 waves of focus diversity**

- **JPL's High Contrast Imaging Testbed provides a highly stable test environment for WFS&C and Coronagraphy**
  - Demonstrated λ/5,000 WFS&C performance
  - Demonstrated 6.4 x 10-10 contrast at the 4^{th} Airy ring, and 10% bandwidth centered at 800 nm

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

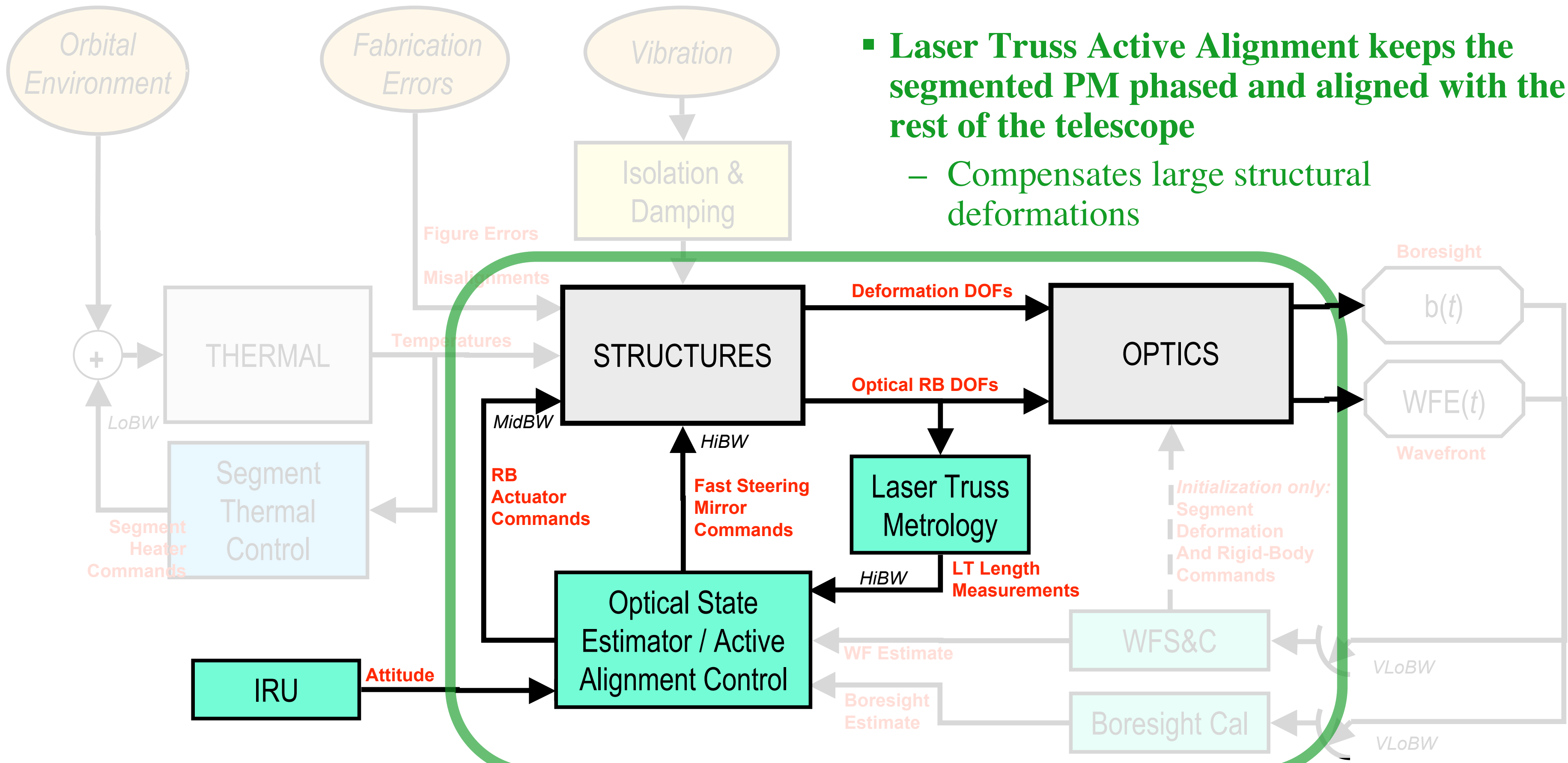
Thermal Control Preserves PM Figure



- Wavefront Sensing & Control sets segment figure and alignment
  - Initially, and then periodically during ops
  - Update frequency will depend on figure and Laser Truss drift rates

- **Segment figure is thermally stabilized**
  - Passive Athermalization: keeps WFE/°C very low
  - Local Segment Thermal Control: PM segment temperatures are kept constant using heaters integrated with segment structure

Laser Truss Keeps All Optics Aligned



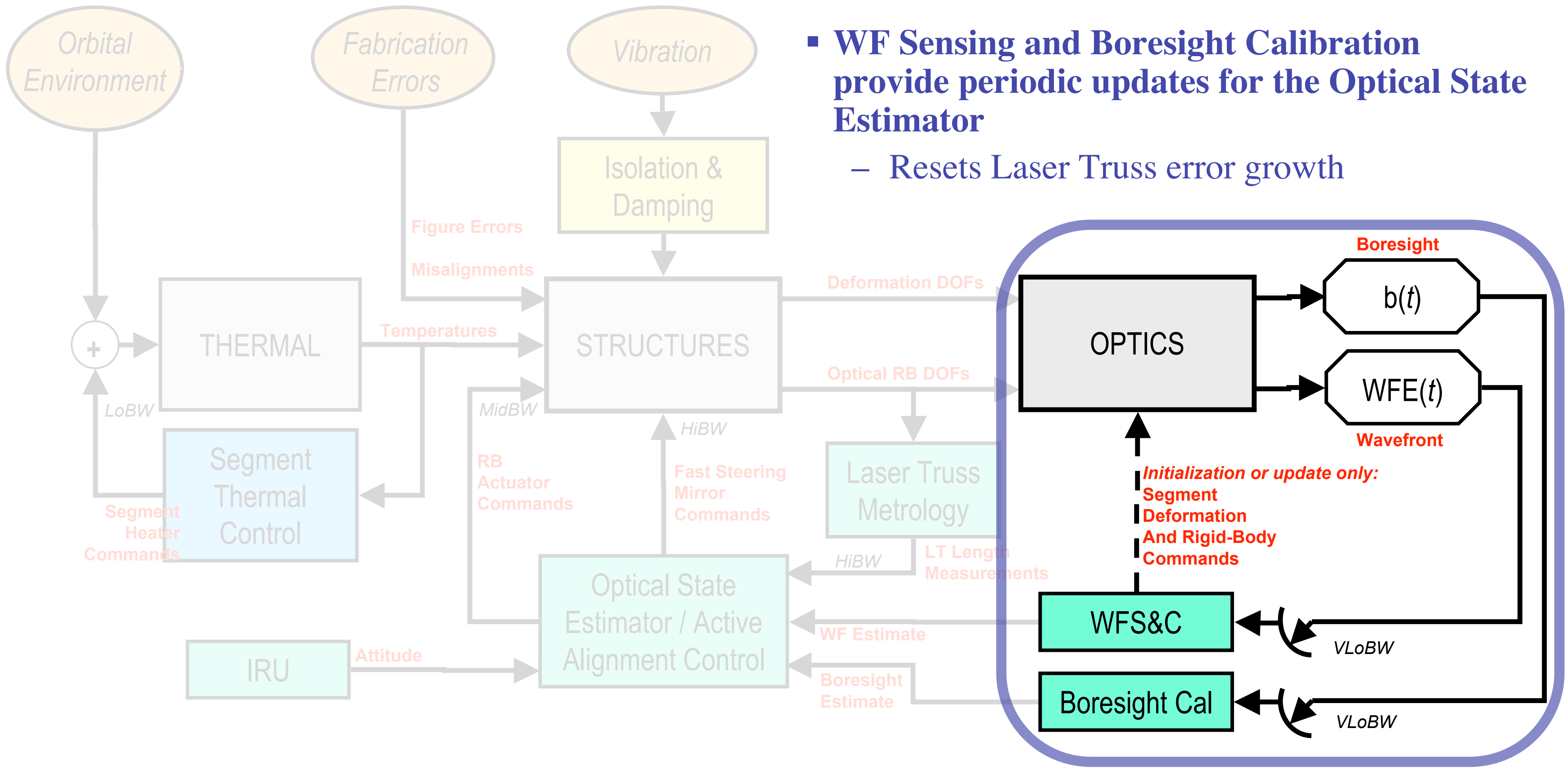
- **Laser Truss Active Alignment keeps the segmented PM phased and aligned with the rest of the telescope**
  - Compensates large structural deformations

- **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**

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

WFS&C Updates

- **WF Sensing and Boresight Calibration provide periodic updates for the Optical State Estimator**
  - Resets Laser Truss error growth



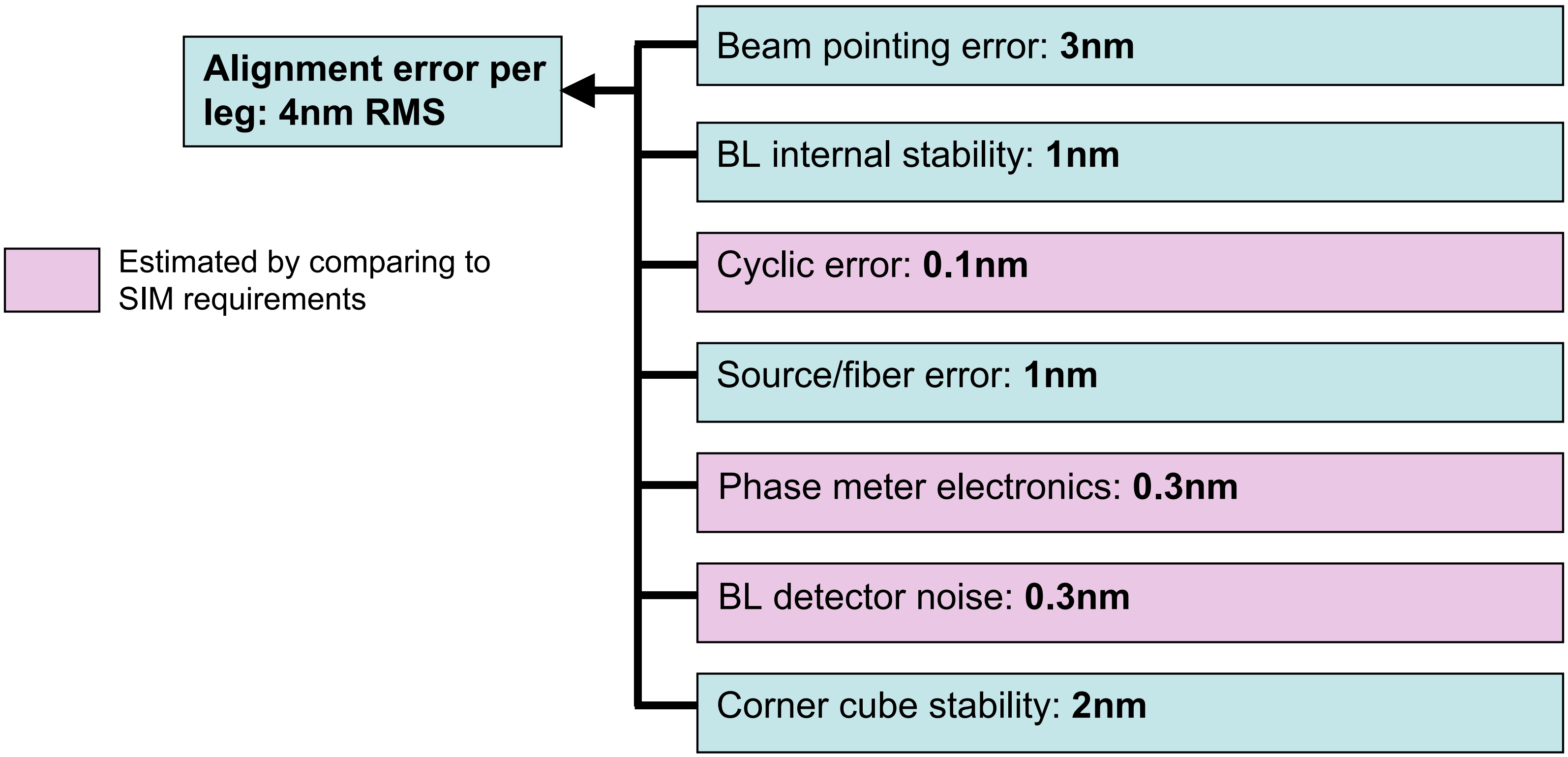
- Laser Truss measurements at 100 Hz are processed in a Kalman Filter to estimate the perturbation state of all the optics
- Estimated state is fed back to control WFE (< 1 Hz) and boresight (< 10 Hz)

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

Notional Metrology Error Budget

- **Notional LDG error budget, based on extrapolated SIM and R&TD data**



- **This level of performance is much worse than was *demonstrated* by SIM**
- **However…**
  - Much smaller, lighter-weight components will be needed
  - Long-term laser frequency stability will be required

Conclusion

- **Our baseline utilizes developing and realized active optics technologies to provide a plausible development path to diffraction limited performance at 500 nm wavelength for ATLAS-T16**

- **Planet Imaging will require further active optics technology development**
  - Large lightweight segments
  - Smaller, lighter, higher performance LDGs
  - On-board closed-loop extreme WF sensing and control
  - Broad-band coronagraphy