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WFIRST/AFTA Coronagraph LOWFSC Status and Recent Lab Test Results

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Outline

- Low order wavefront sensor (LOWFS) status
- LOWFS sensor performance analysis
- Low order wavefront control loop simulation
- Line-of-sight jitter loop simulation
- LOWFS testbed including OTA Simulator
- Initial LOWFS sensor in-air test
- Summary

WFIRST-AFTA Coronagraph Functional Block Diagram

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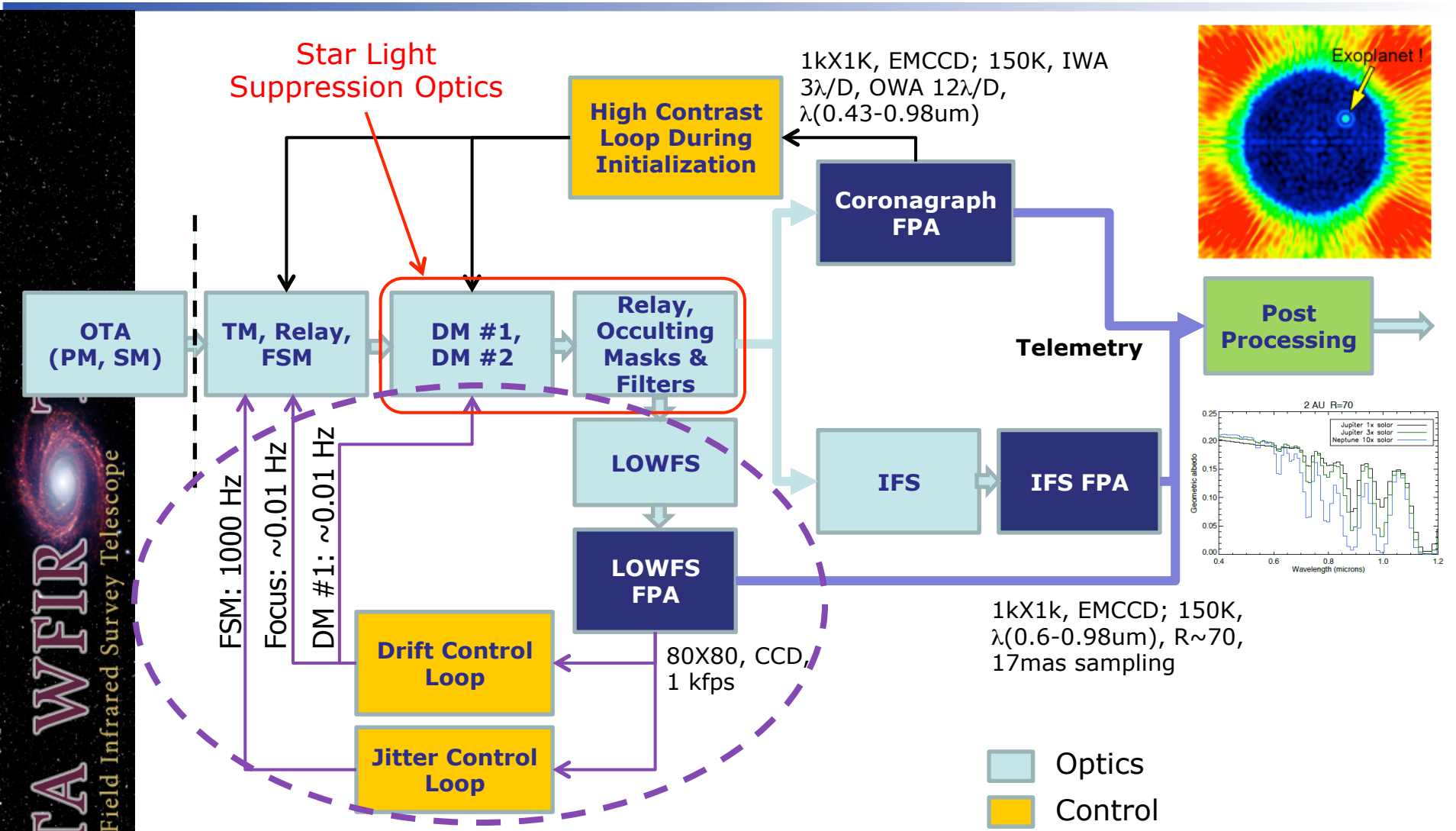

The function of LOWFS is to measure the LoS jitter and the low order WF changes

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WFIRST/AFTA LOWFSC Status Update

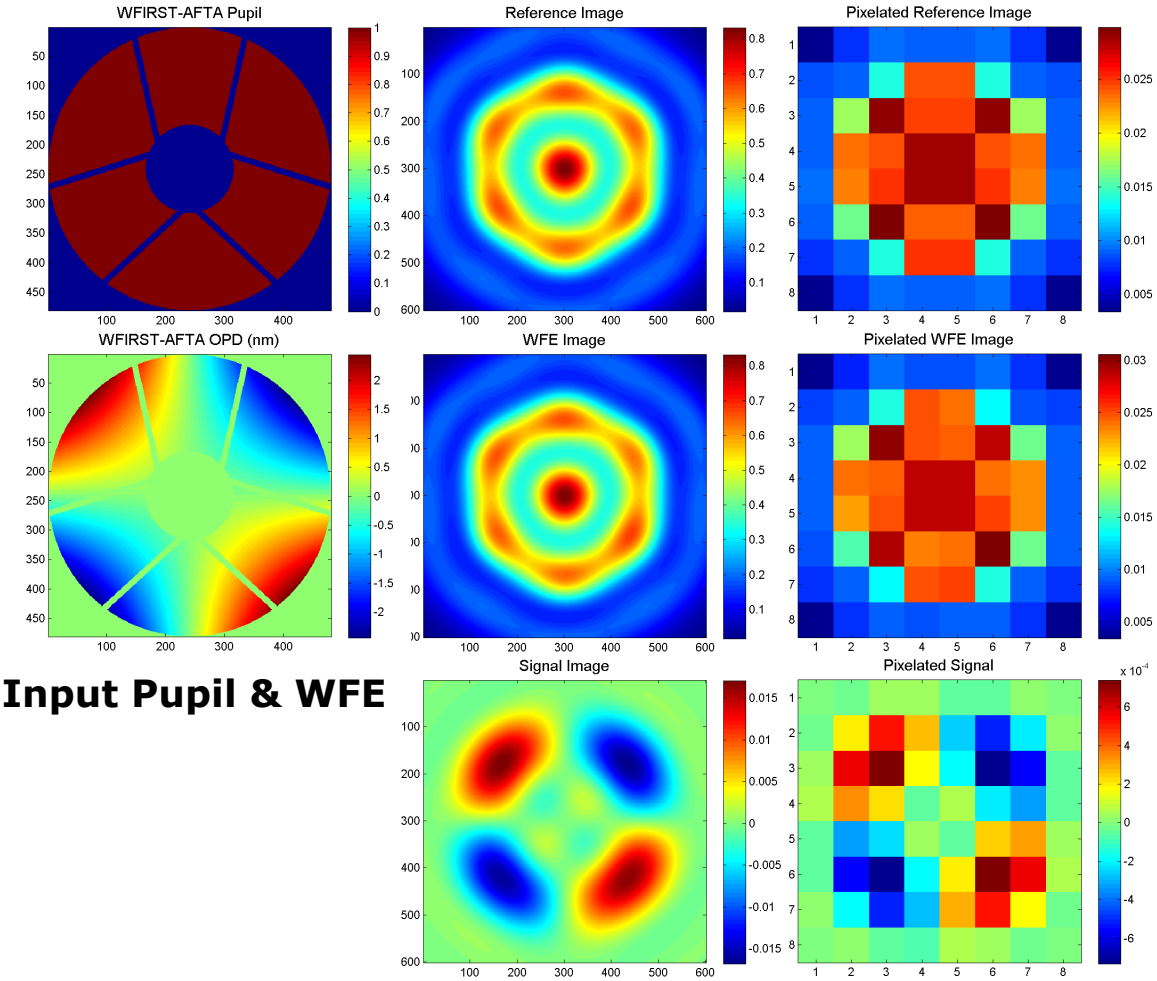
- WFIRST/AFTA LOWFSC has chosen Zernike wavefront sensor (ZWFS) with phase dimple built onto the coronagraph star rejecting mask
  - The Masked-PSF WFS was studied but not selected mainly due to the feasibility of mask fabrication with current coronagraph design
- Extensive modeling and analysis of ZWFS have been carried out to understanding the performance of the sensor
  - Stellar magnitude, pupil sampling, wavelength bandwidth, phase mask size variation / fabrication error, detector flat field error, image registration error
- Built a model to analyze coronagraph performance with the LOWFSC sensing and correcting the low order WFE using DM
  - The base line LOWFSC now includes using DM to correct LO-WFE, in addition to FSM line-of-sight correction and focusing mirror focus correction
- Line-of-sight jitter suppression servo now includes feedforward loop using the knowledge of wheel speed to correct the high frequency harmonic jitter from the reaction wheel
- Designed a LOWFSC testbed including OTA Simulator. LOWFSC testbed I&T is about to start
  - Finished the FSM characterization and LOWFSC CCD camera tuning is on-going
- Conducted ZWFS in-air tests using HLC mask which have demonstrated the LOWFS sensor is capable of detecting sub milli-arcsecond tilts

ZWFS Analysis Approach

Diffraction model using "Semi-Analytical Method (SAM) or FFT:

- Generate ZWFS intensity output (reference) with zero input phase and down sampled to 8x8 pixels
- Add photon noise and detector read/ dark noise and down sample to 8x8 pixels
- Generate ZWFS intensity output with aberration from input phase error Φ
- Add photon noise and detector read/ dark noise and down sample to 8x8 pixels
- Subtract out reference frame and reconstruct the sensed phase error using signal-to-Zernike-coefficient matrix which is pre-calculated at noise-free case
- WFE (phase error) is computed with pseudo inverse of signal-to-Zernike coeff matrix

Example on ZWFS Signal (FFT Model)



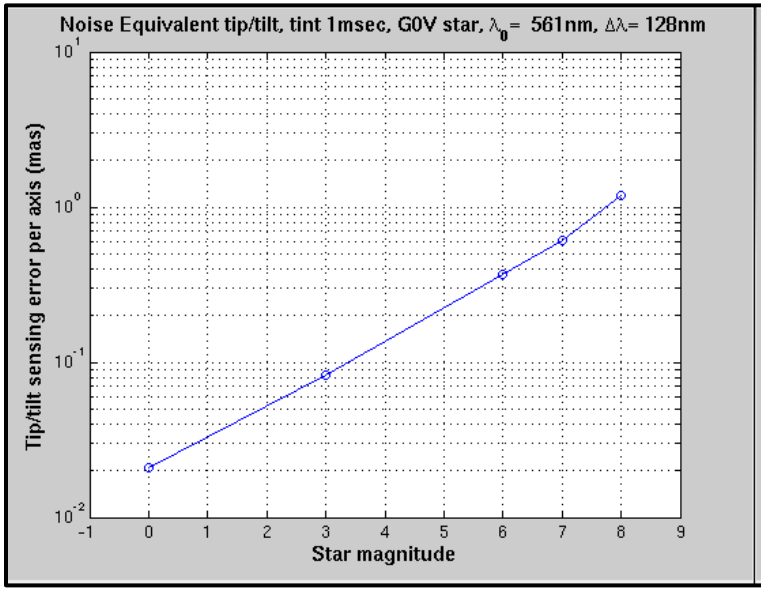
Input Pupil & WFE

High Resolution ZWFS Signal

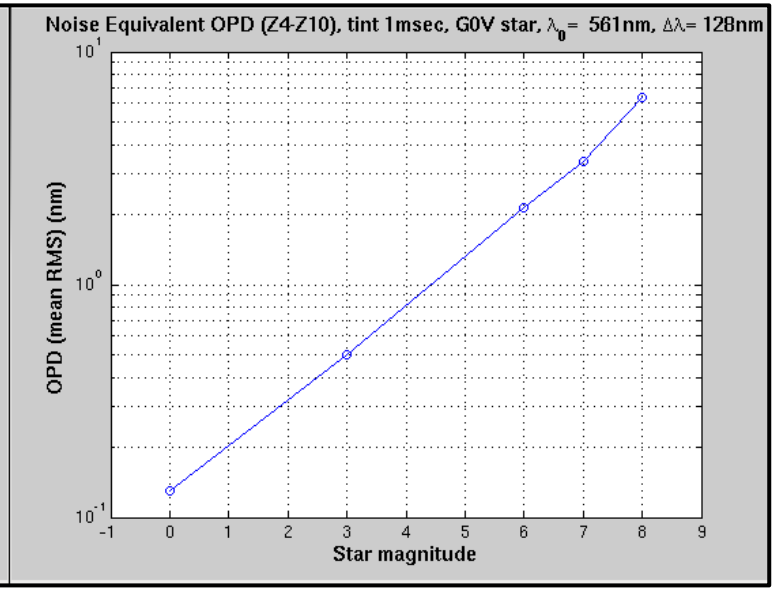
Pixelated ZWFS Signal

ZWFS Noise Performance with WFIRST/AFTA-C HLC

Noise Equivalent Angle (tilt)



Noise Equivalent Low Order WFE



- Use HLC 20140623-139 occulting/ZWFS mask design for this analysis
- Use K0V star spectral profile. ZWFS wavelength band shown in the plot: 561 nm ± 64 nm
- Assume WFS CCD camera exposure of 1 msec (read out at 1 KHz frame rate)
  - Low order WFE from thermal drift varies much slower which allows sensor's images to be averaged to improve S/N
- Analysis includes camera (CCD39) QE, readout noise, and dark current specifications
- Each result data point is a mean of 100 Monte-Carlo realizations
- Noise performance is very similar with & without WFE presence
- A ZWFS model is built for closed loop simulation

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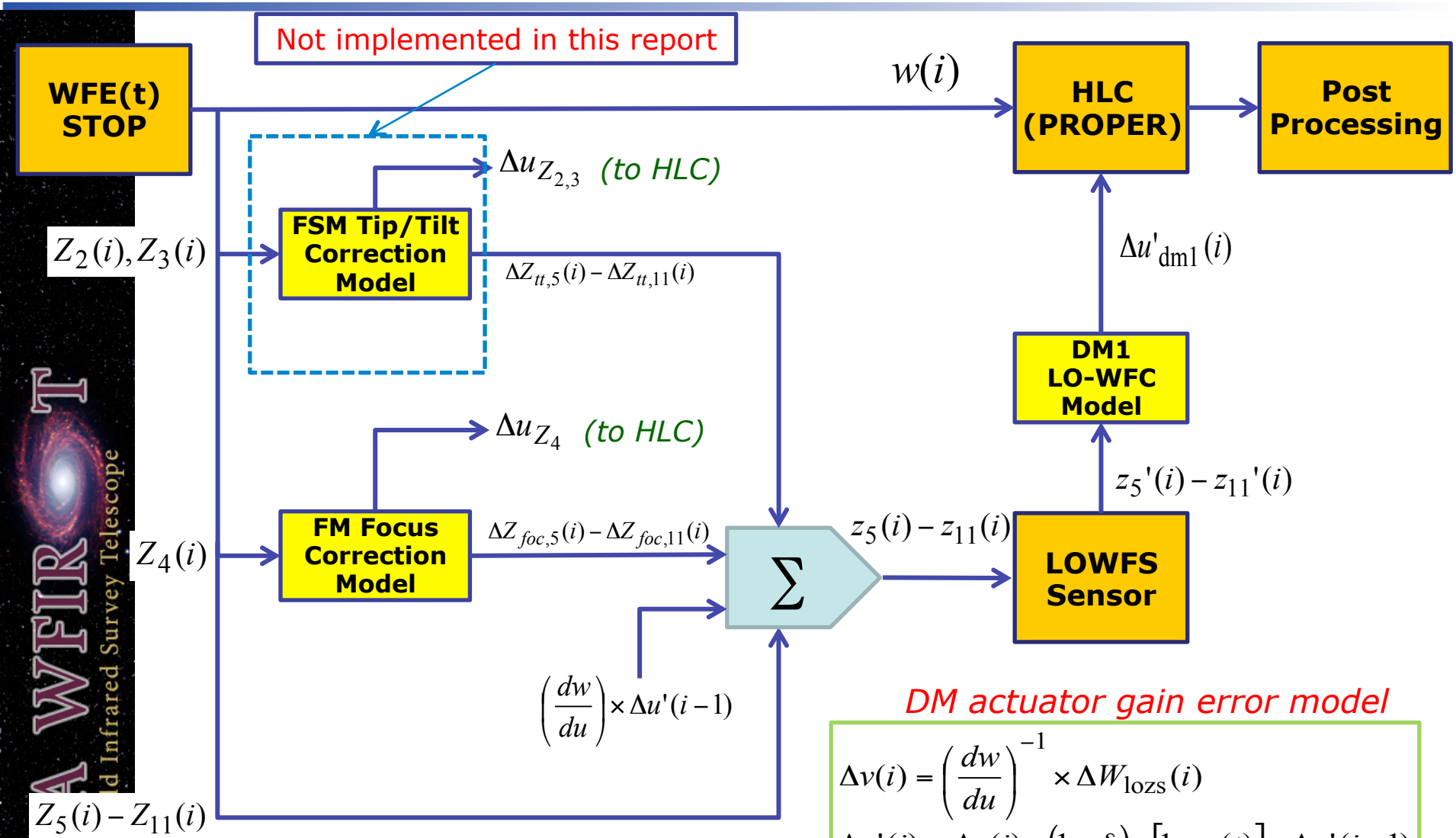
LOWFSC DM Correction Simulation Block Diagram



DM actuator gain error model

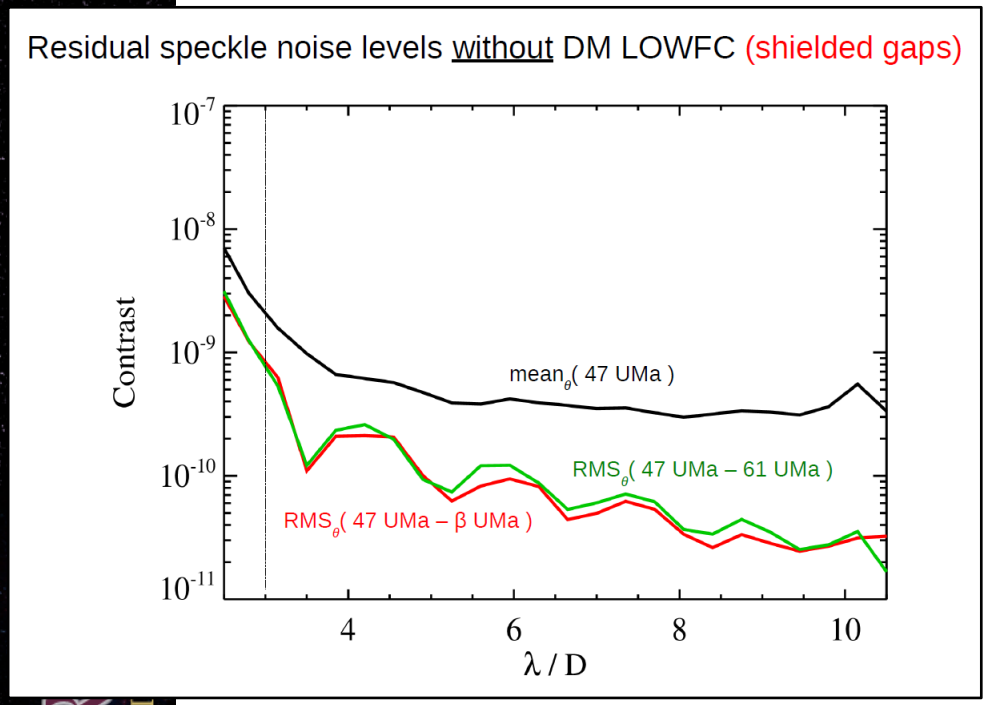
$$\Delta v(i) = \left(\frac{dw}{du}\right)^{-1} \times \Delta W_{\mathrm{lozs}}(i)$$

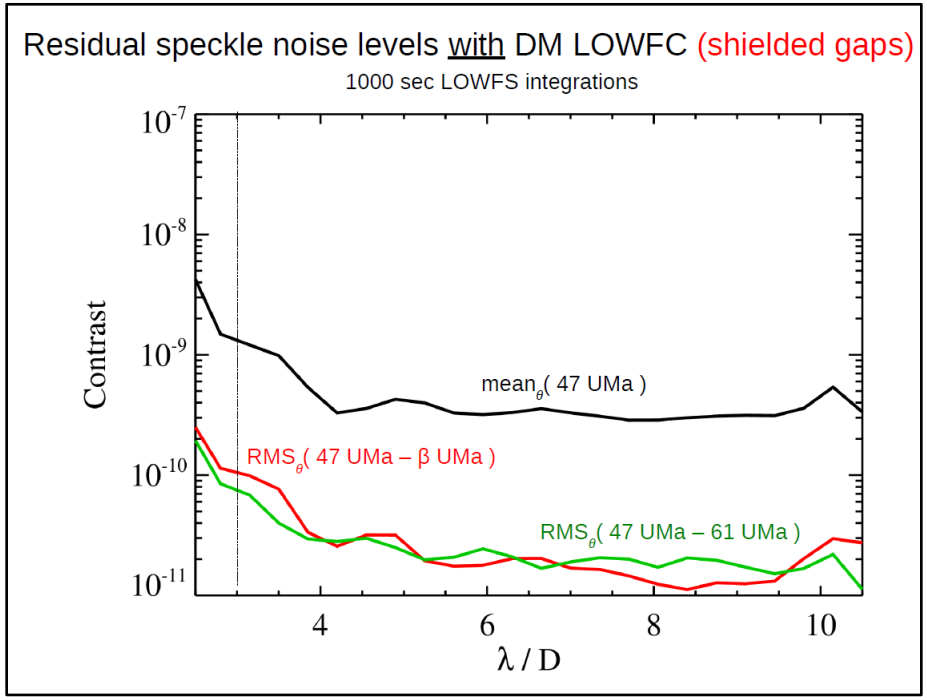
$$\Delta u'(i) = \Delta v(i) \times (1+\delta) \times [1+\gamma(t)] + \Delta u'(i-1)$$

Static gain errors

Time-variant gain errors

Residual Speckle Noise Levels with DM LOWFSC Correction

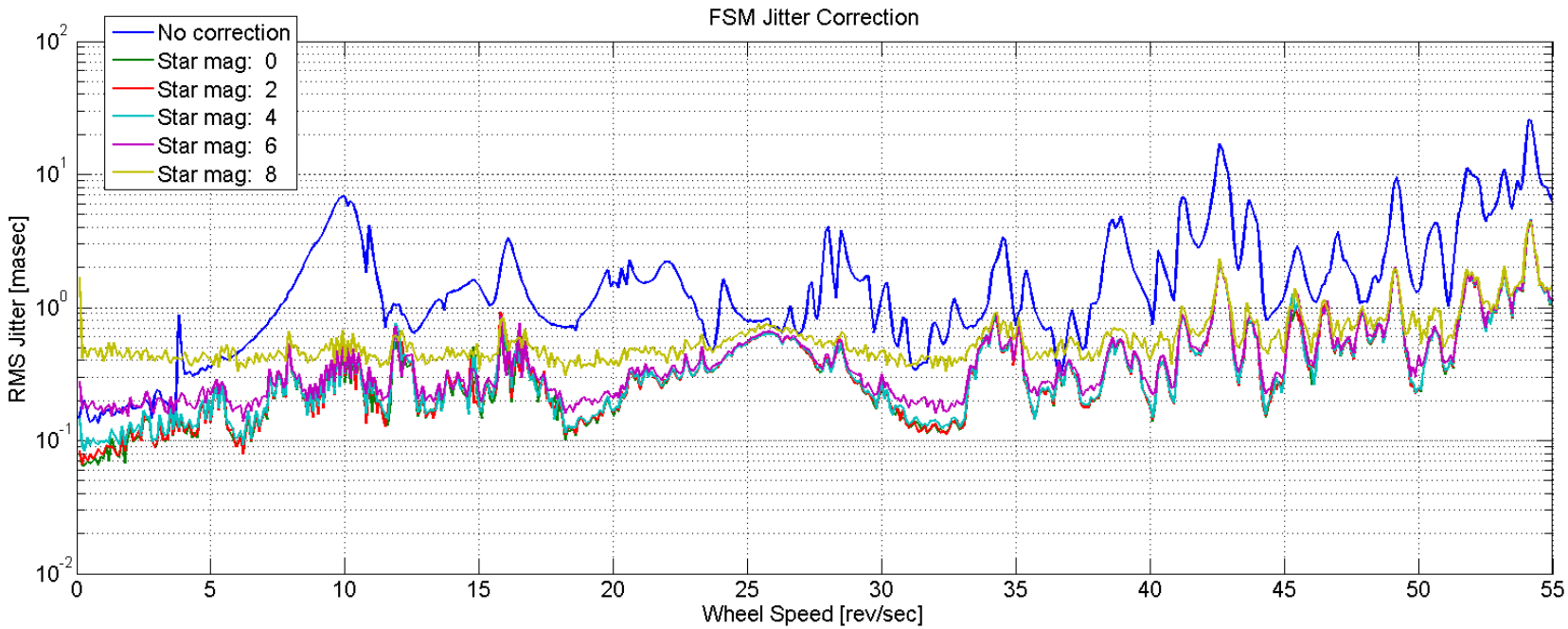




- Mean contrast and rms residual speckle noise for OS3 WFE drift from WFIRST/AFTA Cycle 5
- DM #1 to correct the low order WFE after tilt and focus (Z5 – Z11)
- Jitter and focus is removed here to understand the DM loop
- HLC 20140623-139 coronagraph
  - X polarization (EFC optimized for X only)
  - Broadband 523-578 nm images constructed using 9 monochromatic images

Simulated FSM Loop Performance (X Direction LoS Jitter)

- Using WFIRST/AFTA Cycle 5 RAW jitter estimates as disturbance input
  - single worst case wheel
- Feedforward tonal estimator (with 3 harmonics)
- Use ZWFS sensor noise model
  - LOWFSC camera running at 1 KHz



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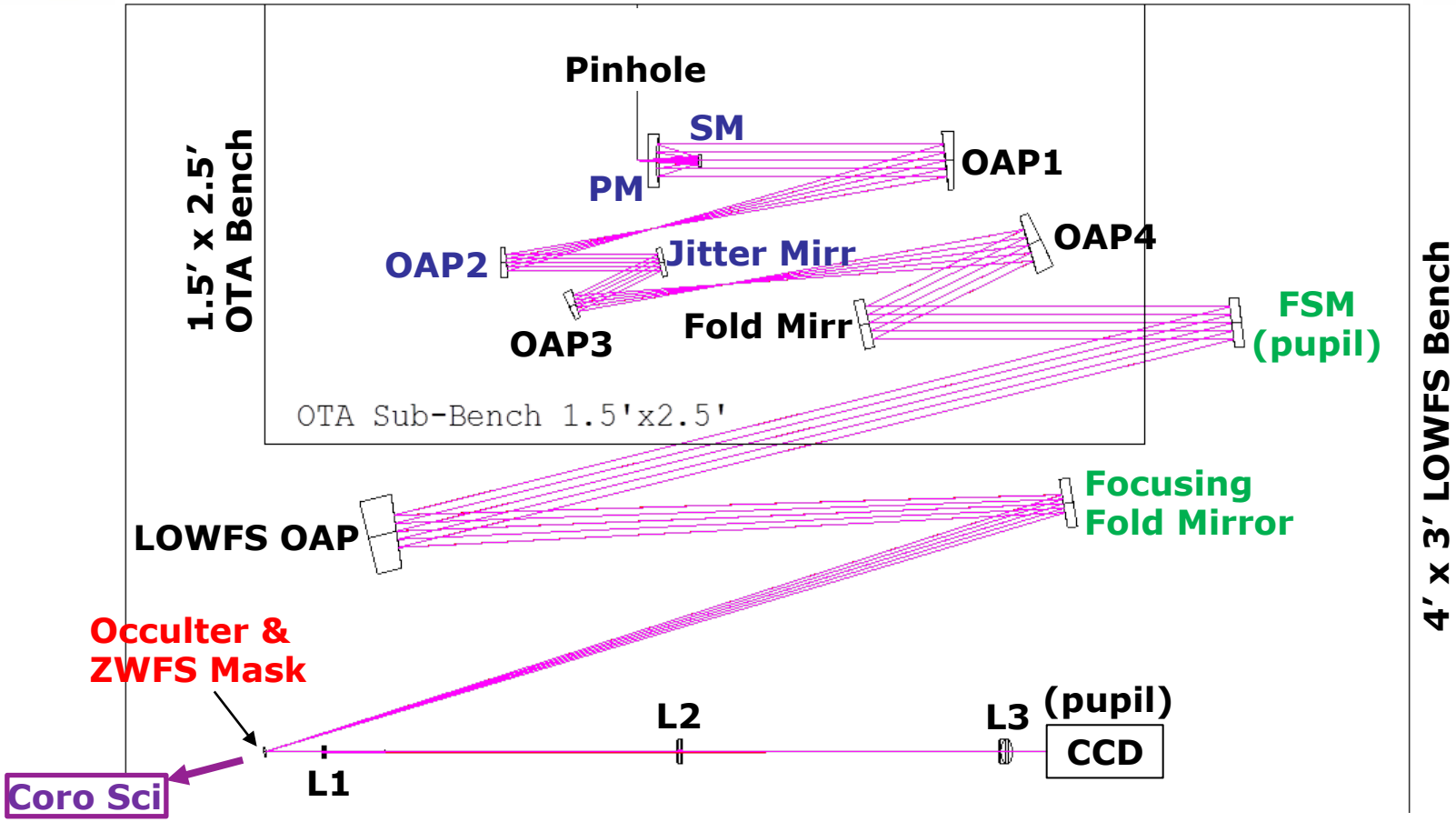
OTA Simulator and LOWFSC Testbed



- OTA simulator consists of miniature WFIRST-AFTA telescope, relay optics, and a small jitter mirror conjugated to the pupil (PM)
- OTA simulator uses the precision motion of the powered optics to simulate the telescope jitter and drifts
  - Line-of-sight jitter is simulated by a small mirror conjugated to pupil on a PZT stage
  - Small (~nm) low order (focus, stigmatism, coma, and spherical) wavefront error can be generated by moving powered optics on OTA simulator (PM, SM, and OAP2) using PZT actuators
  - All PZT actuators have strain gauge to ensure the precision of their motion

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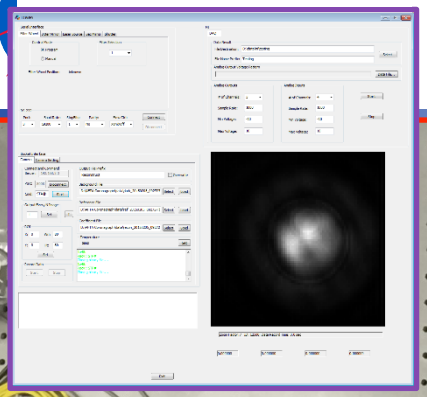
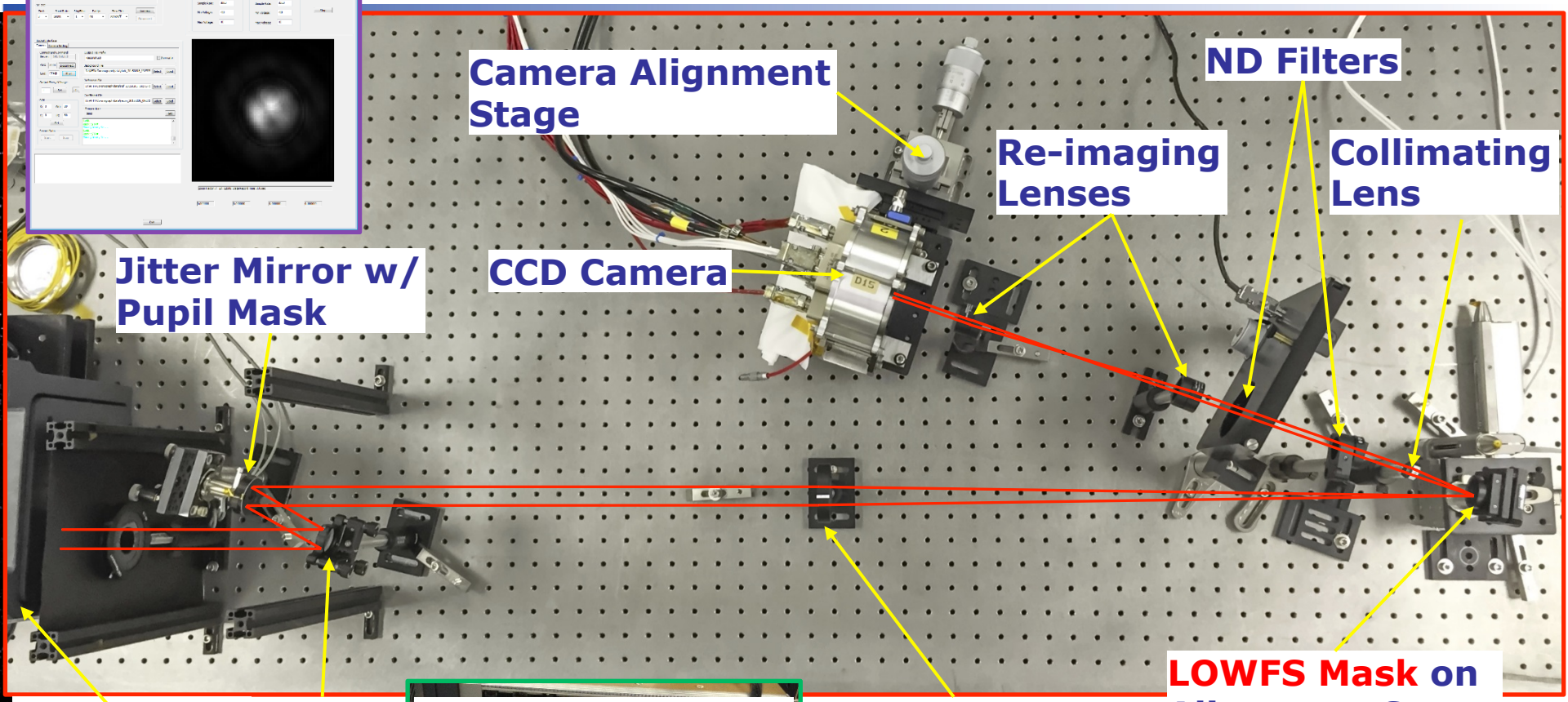
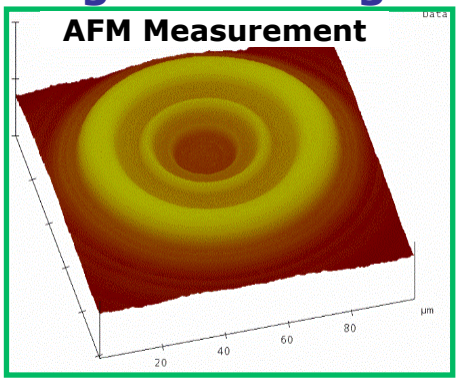
HLC ZWFS Mask In-Air Test Lab Setup

Testbed SW GUI





Camera Electronics

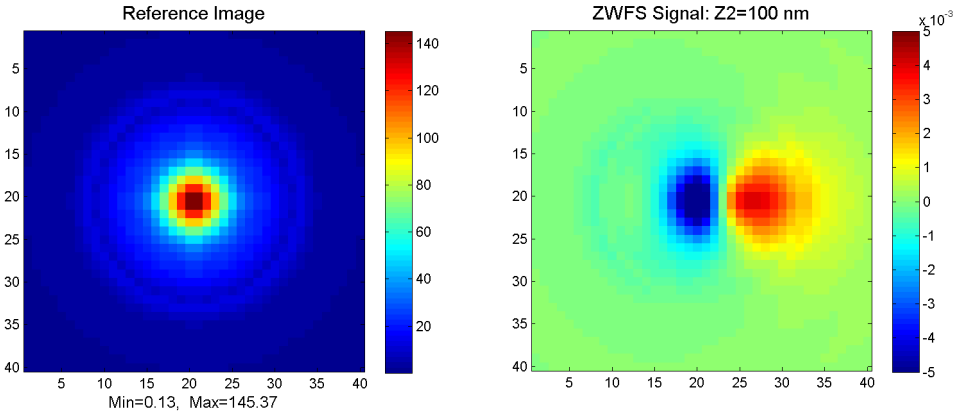


AFTA Wide-Field

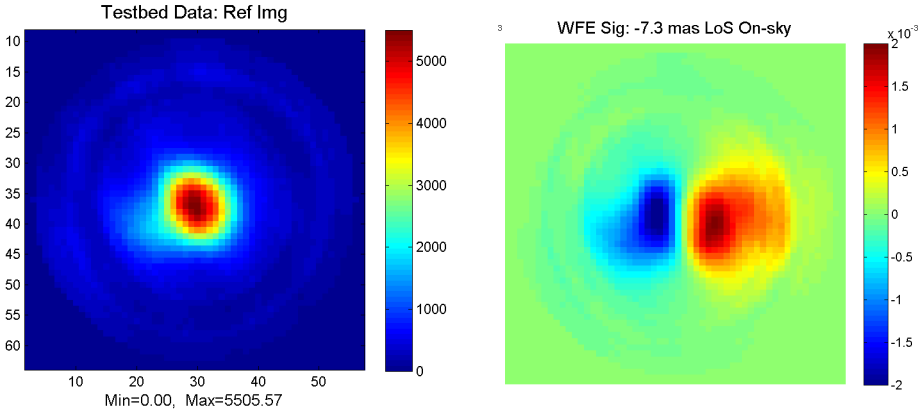
Modeled ZWFS Image & Signal vs. Test Data

- Model include the reflectance and phase profile based on the AFM measured occulting mask
- Modeled data is pixelated to 40 pixels across pupil to match the testbed image sampling
  - Model does not include the (small) lens aberration or air turbulence
  - The model image includes 4% substrate reflection outside Nickel spot
  - Model does not include diffused reflection of pupil mask on JM
- The testbed data matches well to the model prediction

Modeled Image and ZWFS Signal



Testbed Image and ZWFS Signal



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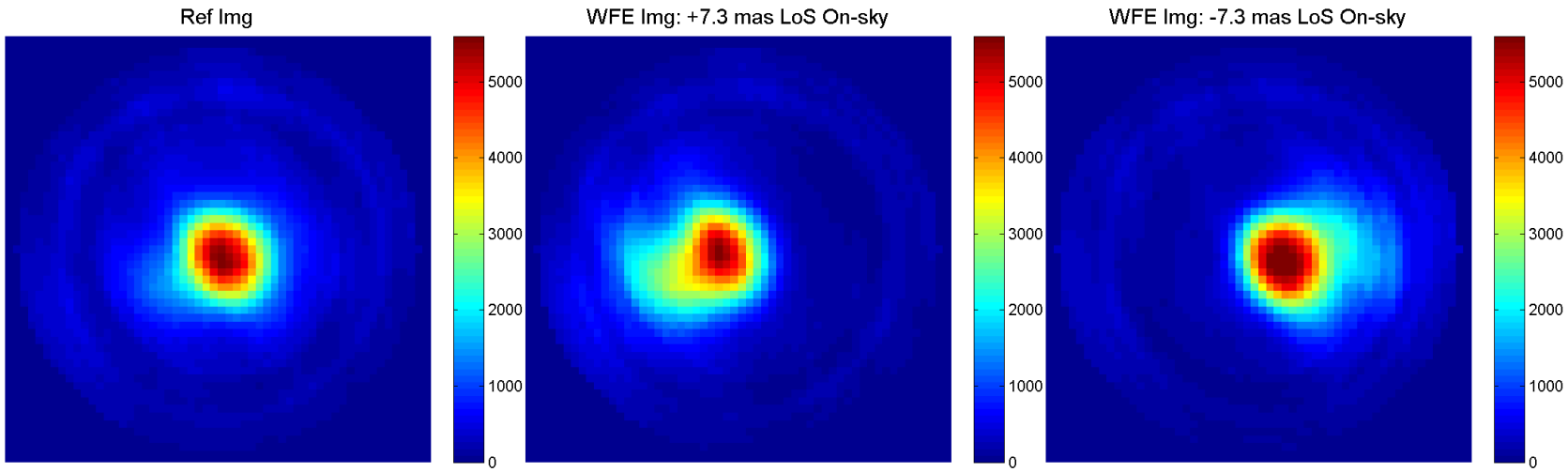
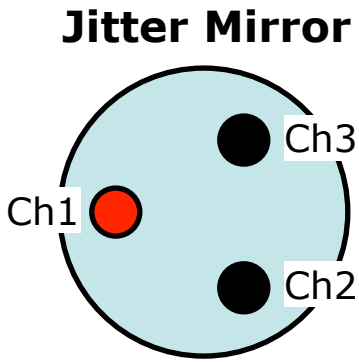
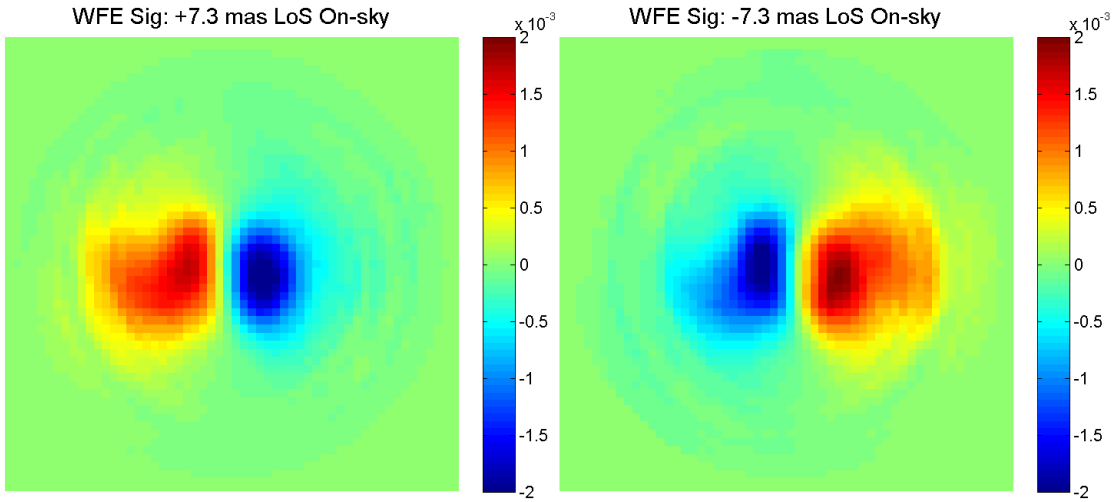
ZWFS Data with PZT Tilt Mirror







- Tilt is introduced by Jitter Mirror (JM) on a 3-axis PZT stage
- JM tilt has been calibrated with Zygo and WF tilt has been converted to on-sky LoS angle

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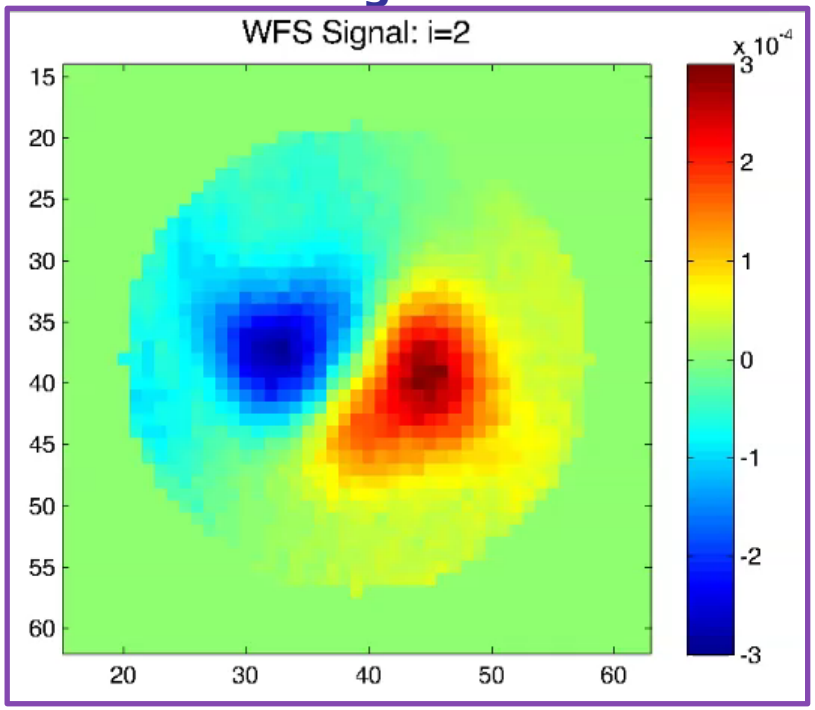
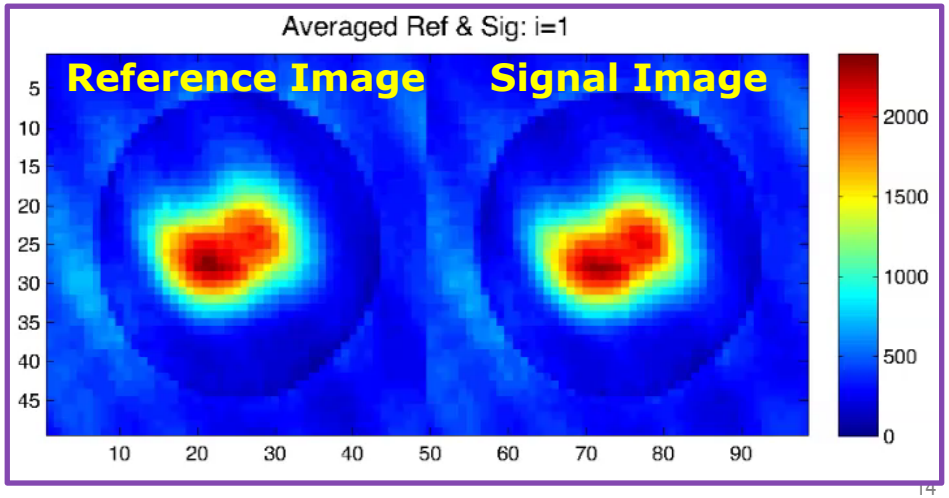
Testbed data – ZWFS Signals: Lab Seeing Movie

- CCD camera running at 1 KHz
  - Total ~50 sec recorded
- First 100 frames (0.1 sec) are averaged as the reference
- Rest of frames are averaged every 100 frames (0.1 sec) and used as the WFE signal images
  - Differential images of subsequence images is the ZEFS signal
- The movie shows the lab seeing over ~50 sec with 0.1 sec step
  - The movie plays at the same speed of ZWFS.
  - The ZWFS absolute amplitude is proportional to WFE
  - ZWFS signal plot colorbar range (±3e-4) is equivalent to ±1.1 milli-arcsec on-sky LoS

ZWFS Signal Movie

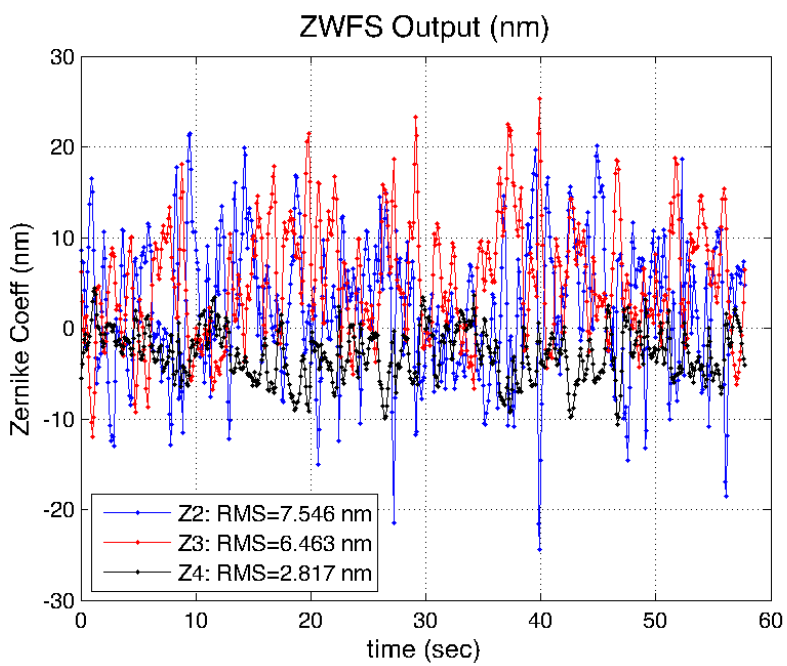


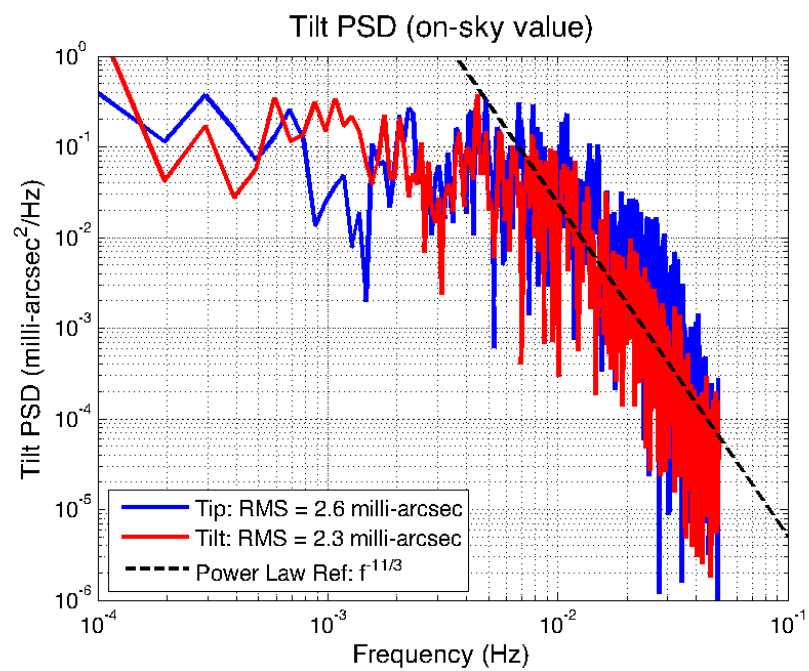
ZWFS Image Movie



HLC ZWFS In-air Test

- Recorded ZWFS signal (shown in the movie in previous page) is reconstructed for WFE in term of Zernike coefficients
  - $Z = R * \Delta I$, where Z (11x1) is the sensed WFE Zernike terms, currently first 11 Zernike terms; R is reconstruction matrix (11x6400), currently derived using ZWFS model; and ΔI is the vectorized differential image (6400x1) between the normalized signal and reference images
- The plot on the left shows the time traces of measured WFE in tilts (Z2 and Z3) and focus (Z4).
  - Their RMS values are labeled in the legend
  - The ZWFS measurement shows the atmospheric turbulence in the lab
  - Tilt is dominant WFE
- The plot on the right shows is the PSD vs frequency of measured tilt, convert to on-sky LoS tilt





LOWFSC Summary

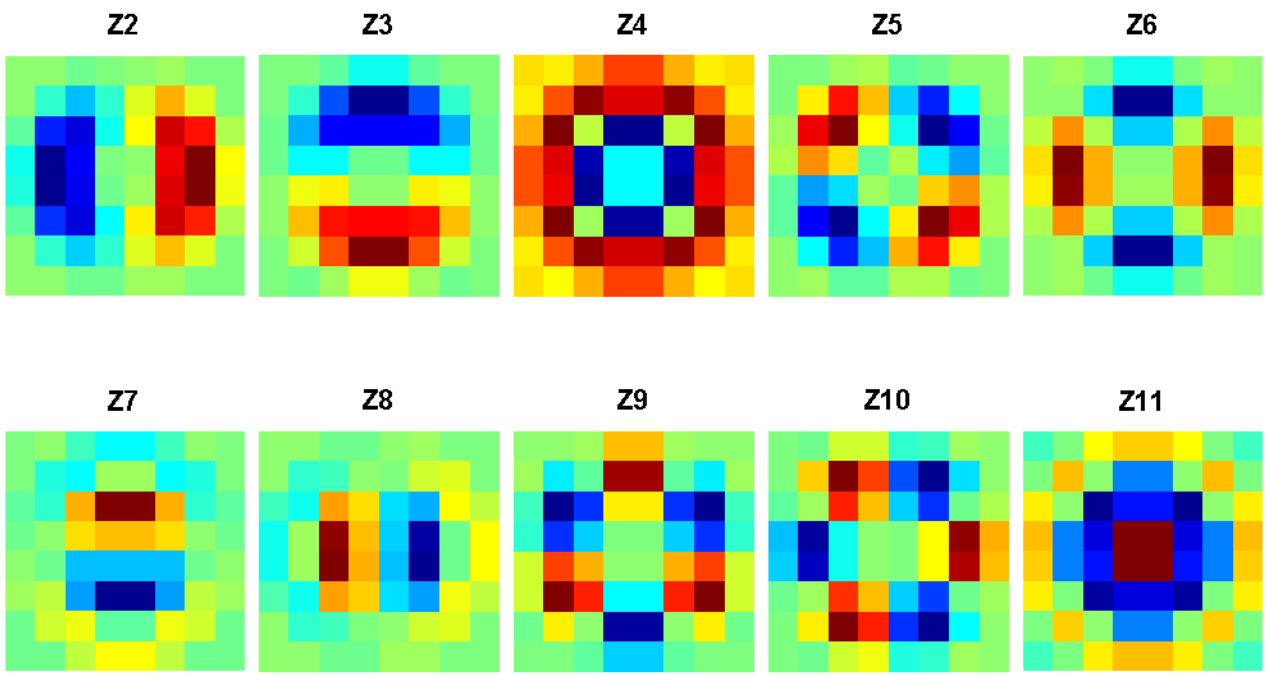
- Zernike phase contrast WFS is used to sense and correct the low order wavefront drift and line-of-sight jitter using the rejected star light from the coronagraph
- Working in differential mode the ZWFS can provide the sensitivity needed for the coronagraph
- Simulation of LOWFSC jitter suppression and low order WFE correction using the observatory disturbance are on-going and preliminary results are very encouraging
- A testbed is being built to simulate WFIRS-AFTA telescope jitter & drift and to test the LOWFSC sub-system
- Early lab results using HLC mask have shown that the LOWFS sensor is capable of detecting sub milli-arcsecond tilt, as needed for WFIRST/AFTA coronagraph to meet its science requirements on-orbit.
- The experiment image and LOWFS signals closely match the model predictions, limited by the uncertainty of lab seeing
- The successful lab test of ZWFS brings the sensor technology to TRL-4

Backup

Zernike WFS Pixelated Signals for Each WFE Modes

Pixelated ZWFS signals of Z2-Z11 WFE modes

- Used for WF sensing
- Noise will be applied on these signals for performance evaluation



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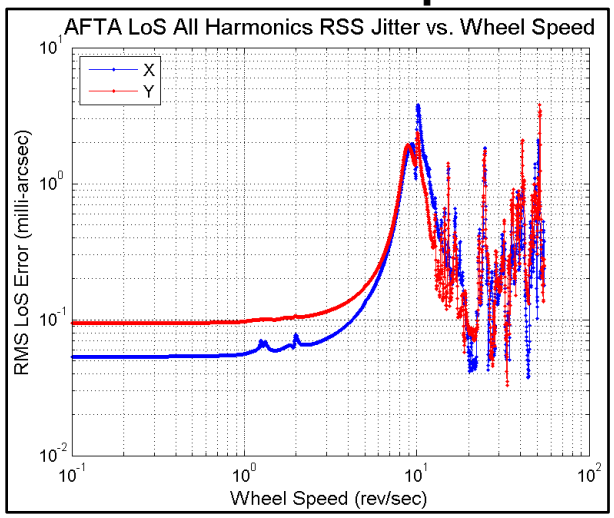
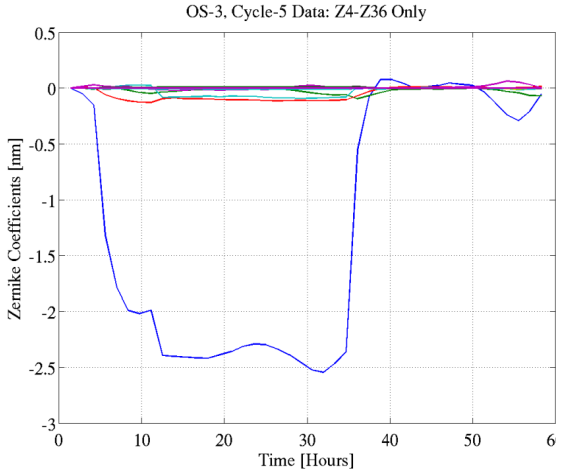
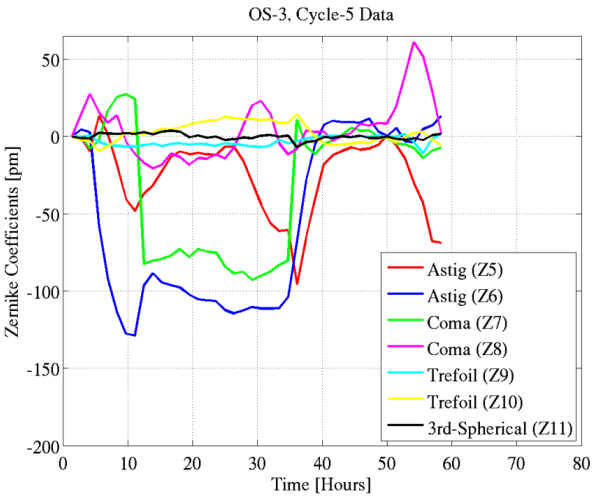
AFTA Telescope LoS Jitter and WFE Drift

- **Line-of-sight jitter and WFE drift from WFIRST/ AFTA Cycle 3 study**
  - Line-of-sight WFE:
    - Drift (<2Hz): ~14 milli-arcsec pointing
    - Jitter (>2Hz): Most around 10 Hz, some high harmonic
  - Thermal drift WFE (Cycle 5):
    - Dominant WFE are focus (Z4) ~2.5nm
    - Significant astigmatism (Z5, Z6) and coma (Z7, Z8)
- **Goal for LOWFS sensor:**
  - Line-of-sight: 0.4 milli-arcsec
    - LoS jitter requirement may be loosened from better coulter design
  - Low order WFE sensing: ~10 pm at much slower rate (> minutes)

LoS vs Wheel Speed



WFE Thermal Drift OS3 Cycle5 include Z4



WFE Thermal Drift OS3 Cycle5 Z5 – Z11