Zernike Wavefront Sensor (ZWFS) Development for Low Order Wavefront Sensing (LOWFS)

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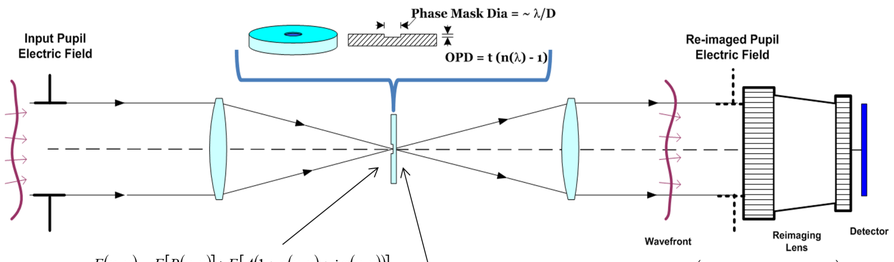
ZWFS concept

$$E(u,v) = P(u,v)\cdot A(1+\varepsilon(u,v))e^{i\varphi(u,v)}$$

$$E(u,v) \approx P(u,v)\cdot A(1+\varepsilon(u,v)+i\varphi(u,v))$$

$$E(x,y) = P(x,y)\cdot A\left(e^{i\theta}+\varepsilon(x,y)+i\varphi(x,y)\right)$$



$$E(\eta,\upsilon) = F[P(u,v)] * F[A(1+\varepsilon(u,v)+i\varphi(u,v))]$$

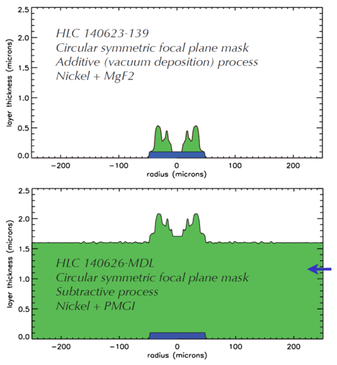
$$E(\eta,\upsilon) = A\,PSF(\eta,\upsilon)e^{i\theta} + A\,PSF(\eta,\upsilon) * F[\varepsilon(u,v)+i\varphi(u,v)]$$

$$I = E\cdot E^* = A^2\left(1+2\varphi+\varepsilon^2+\varphi^2\right)$$

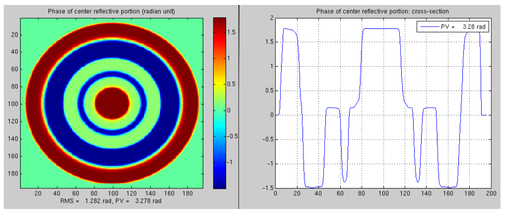
$$\Delta\phi = \frac{(I_{abbr}-I_{ref})}{2A^2} = \frac{\Delta I}{2A^2}$$

ZWFS Mask and Testbed result

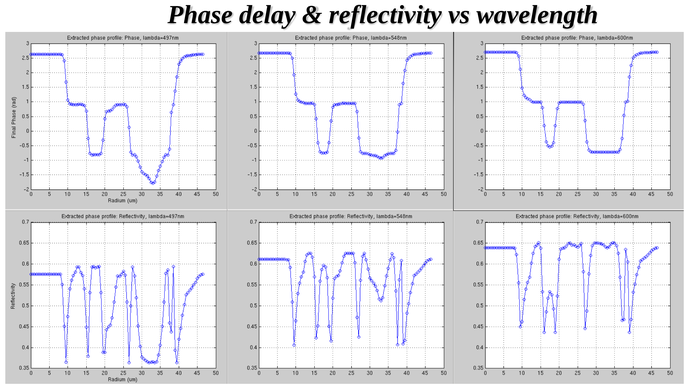
ZWFS mask designs



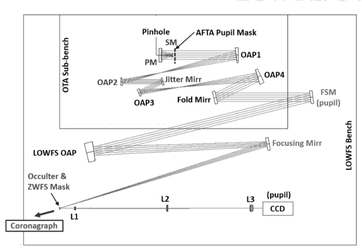
HLC phase plate configuration

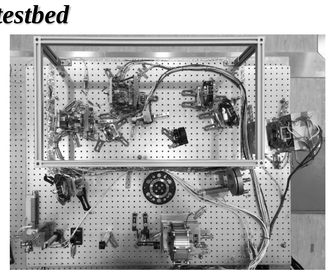


Phase delay & reflectivity vs wavelength

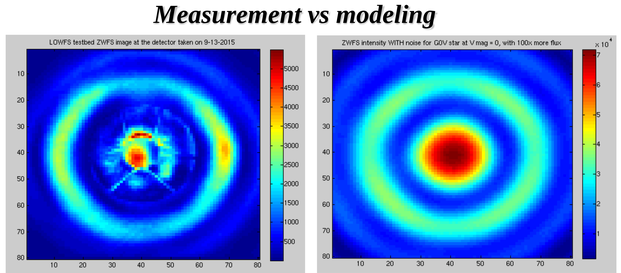


LOWFS/C testbed





Measurement vs modeling

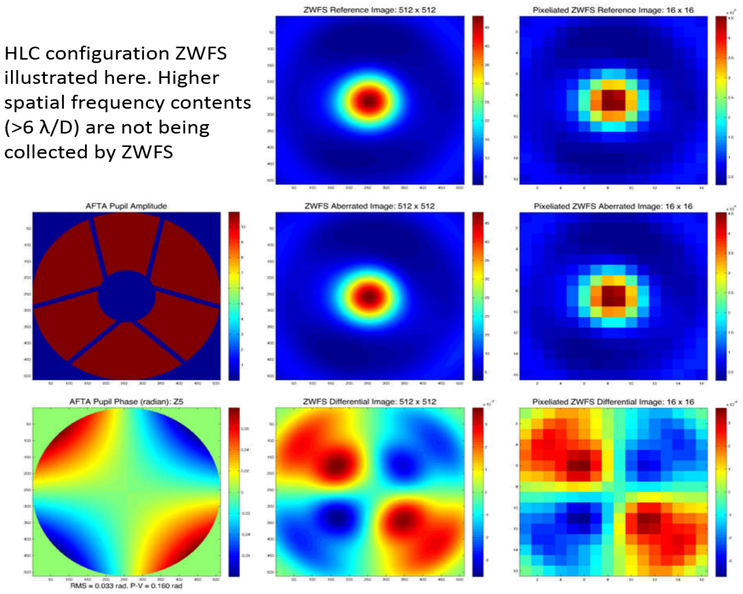


ZWFS analysis

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

1. Generate ZWFS intensity output *zwfsInt0* (reference template) with zero input phase and down sampled to 16x16 for good SNR
2. Adding *zwfsInt0* with photon noise and detector read/dark noise
3. Generate ZWFS intensity output *zwfsInt* with aberration on the input phase Φ and down sampled to 16x16
4. Adding *zwfsInt* with photon noise and detector read/dark noise
5. Subtract out reference template *(zwfsInt - zwfsInt0)* and reconstruct the sensed phase using signal-to-Zernike coeff matrix which is pre-calculated at noise-free case
6. WFE(phase error) is computed with pseudo inverse of signal-to-Zernike coeff matrix

HLC configuration ZWFS illustrated here. Higher spatial frequency contents (>6 λ/D) are not being collected by ZWFS

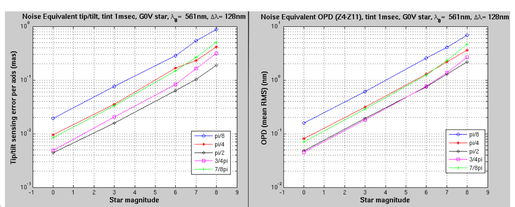


Input pupil & WFE | High Resolution ZWFS signal | Pixelated ZWFS signal

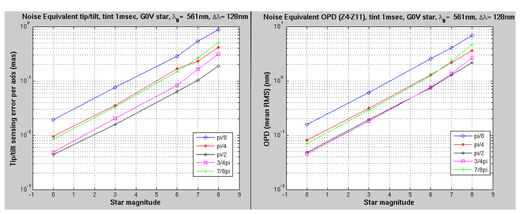
- Photometry
  - G0V star broadband: center at 561nm with 128nm band pass (497nm-625nm)
  - Optics: 2.4m aperture, obscuration ratio 0.185, system transmission 0.243
  - Apply equivalent photo-electron area density at AFTA pupil entrance plane
- ZWFS processor
  - Nominal: simple π/2 phase dimple in the center region of 1.22λ/D
  - HLC: 20140623-139 phase mask profile and corresponding DM1/DM2 settings
  - SPC: Gen1 & Gen2 pupil mask and corresponding bow-tie FPM masks
  - 16x16 sensing array, only Z2 to Z11 modes are sensed
  - ZWFSsig to Zernike coeff conversion matrix trained at 0.1nm WFE
- Detector
  - CCD QE: 0.8, 0.85, 0.87 for 513.5nm, 550.5nm, and 598nm band
  - CCD exposure time: 0.001 sec (1KHz frame rate)
  - CCD noise: Read noise (4 electrons) & Dark current (1 electron@kHz)

The ZWFS sensor noise performance analysis is done as follows:
1) Generate the ZWFS image with no aberrations using ZWFS model
2) Added photon and detector noise to this image in 100 random realizations
3) For each realization, generate ZWFS differential image and reconstruct the corresponding Zernike coefficients. Since the image has no WFE, the sensed WFE is the noise equivalent sensing errors
4) Take the average of the 100 random realizations of sensing error to obtain the mean RMS of tilts (Z2, Z3) and OPD (Z4 to Z11) sensing errors to find the noise equivalent sensing error. Convert the noise equivalent tilt to noise equivalent line of sight angle

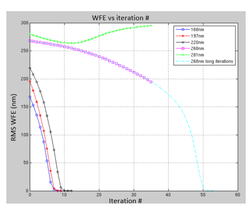
Sensitivity on disk diameter



Sensitivity on disk depth



Maximum correctable WFE



Conclusion

- The WFIRST coronagraph requires a low order wavefront sensing and control subsystem to maintain the coronagraph's contrast stability. The Zernike phase contrast wavefront sensor is selected to sense the low order wavefront drift and line-of-sight jitter using the starlight rejected by the coronagraph's focal plane mask..
- A suite of ZWFS models have been developed, thoroughly tested, and used for sensitivity studies on various noises and perturbations. The modeling analysis suggests that ZWFS sensor is capable of detecting sub milliarcsecond tilt, as needed for WFIRST coronagraph to meet its science requirements.
- A LOWFS/C testbed has been built to simulate WFIRST telescope LoS jitter and wavefront drift. A preliminary agreement between the ZWFS modeling and measurement has been demonstrated in this LOWFS/C subsystem.

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