Performance of Dispersed Fringe Sensor in the Presence of Segmented Mirror Aberrations – Modeling and Simulations

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Outline

- Introduction to segmented mirror coarse phasing with a dispersed fringe sensor (DFS)
- Effect of wavefront aberrations on DFS image and signals
- Modeling study of JWST DHS performance using a scaled gravity sag as the wavefront aberration

Dispersed Fringe Sensor Concept: Image and Signals

- **DFS Grism disperses a broad band source into a spectrum**

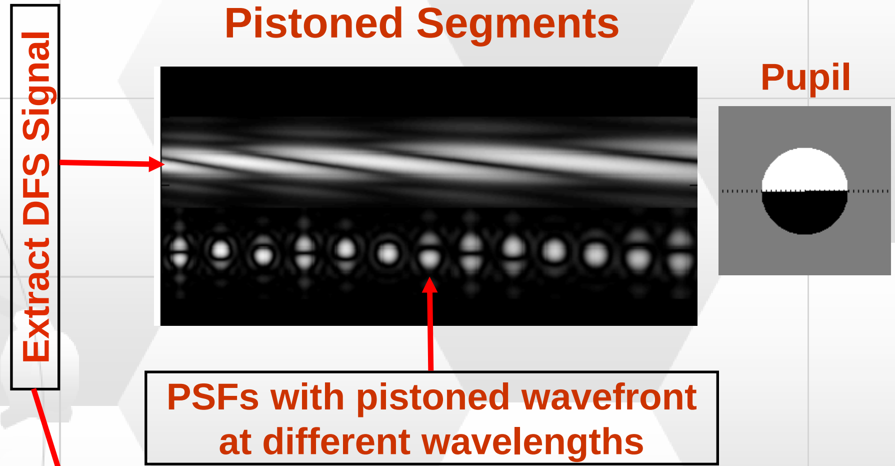
$$\lambda(x) = \lambda_0 + \frac{\partial\lambda}{\partial x}\cdot x = \lambda_0 + C_0 x$$

- **Diffraction of an aperture with segment piston δ forms a PSF with side-lobes shapes dependent on λ**
- **DFS fringe image is formed by incoherently adding all monochromatic PSFs**
- **DFS signal modulation due to the wavefront piston δ**

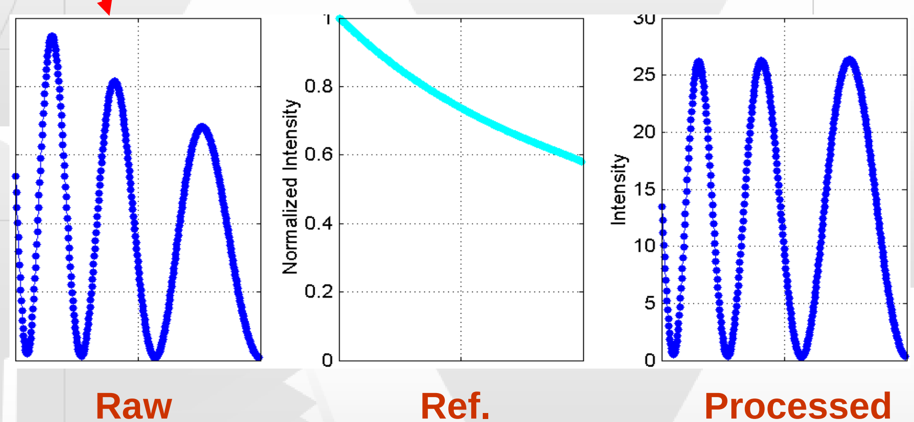
$$I(x,y) = I_0\left[1+\gamma\cos\left(\frac{2\pi}{\lambda(x)}\delta+\varphi(y)\right)\right]$$

- **DFS algorithm uses least-square fit of the DFS signal to solve 4 parameters of fringe equation: I_0, γ, φ, and δ**
- **DFS algorithm has been demonstrated in the laboratory testbeds and Keck Telescope**

Formation of DFS Fringe Image by Pistoned Segments



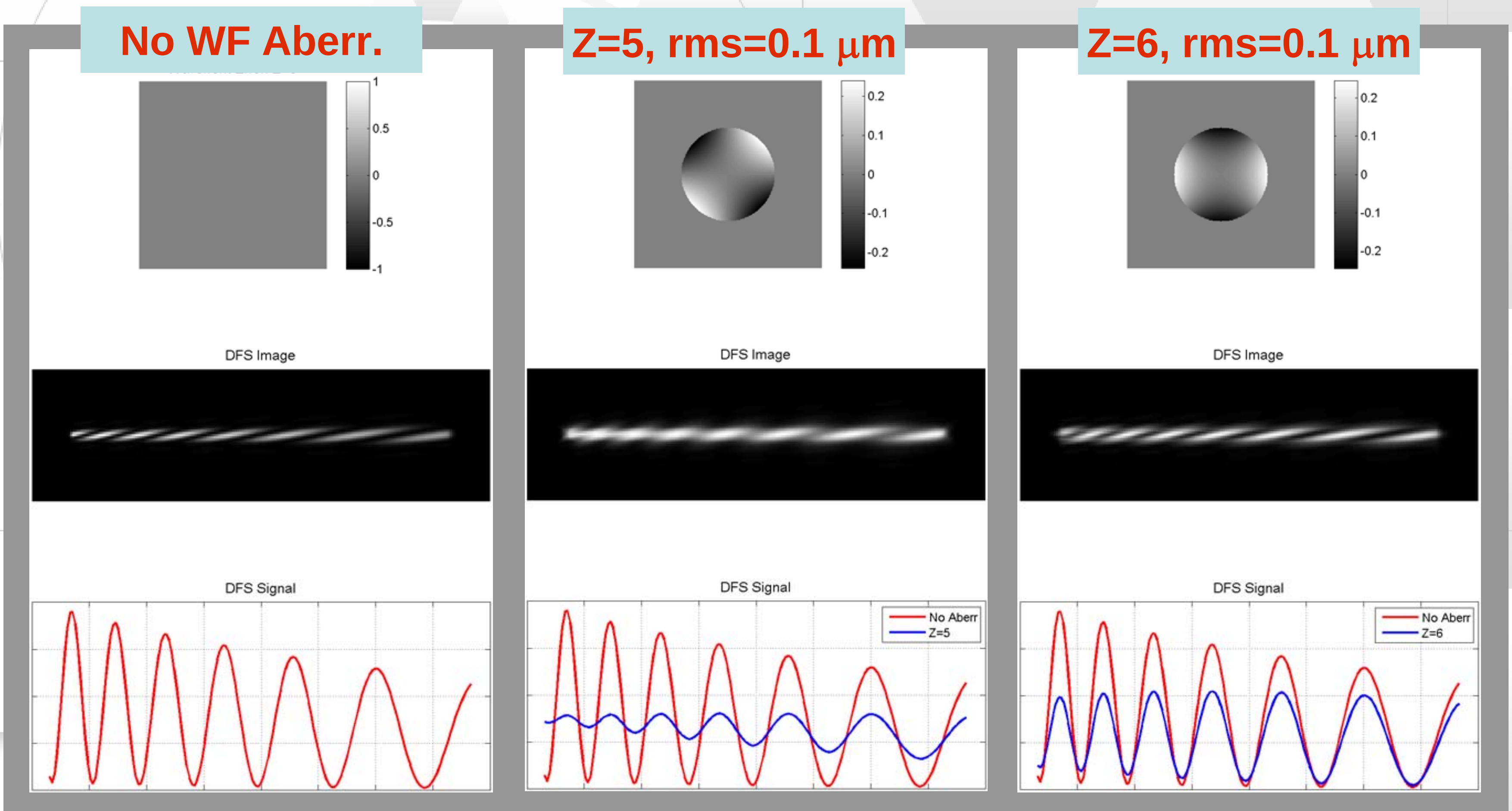
Signals from DFS Fringe



Effect of Wavefront Aberration on DFS Image and Signals

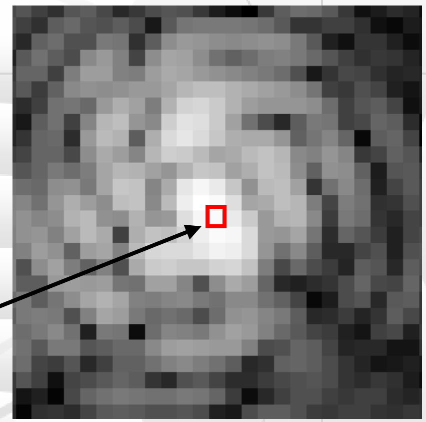
- WF aberration lowers the DFS fringe contrast
- WF aberration effect is stringer in the shorter wavelength end of spectrum
- WF aberration lower fringe signal intensity therefore SNR

- Effect of wavefront aberration also depends on the aberration type
  - Aberrations which forms a larger PSF size along the dispersion direction causes big visibility loss



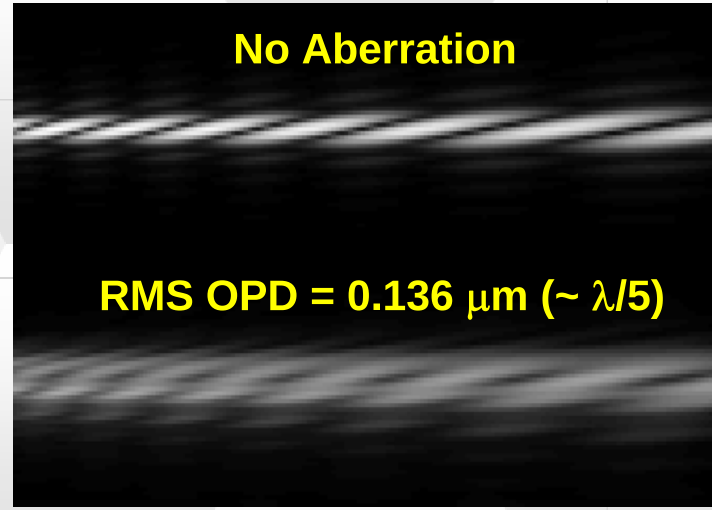
Effect of Wavefront Aberration on DFS Image and Signals

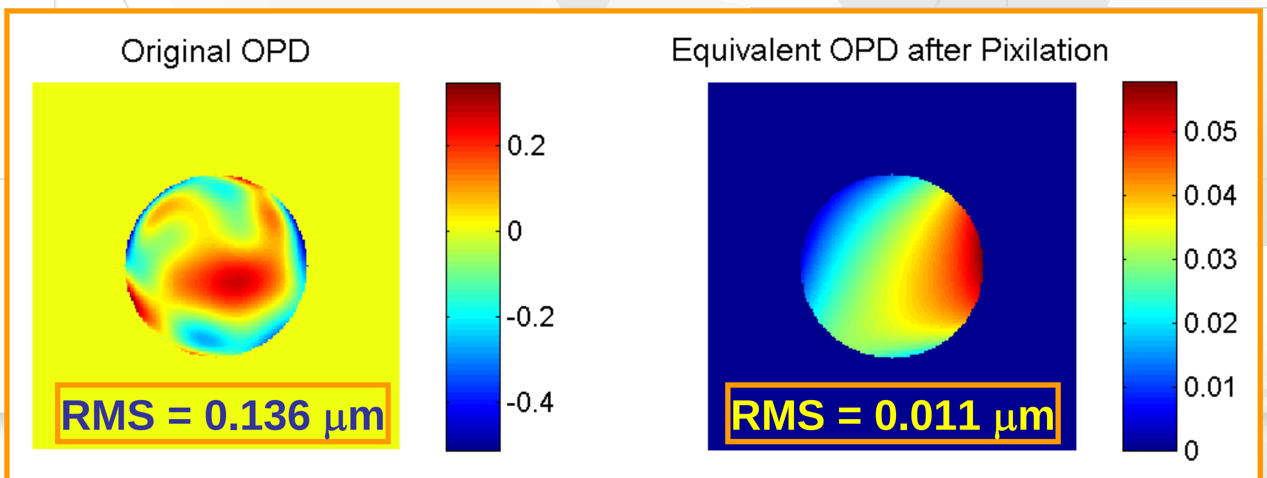
- DFS signal is extracted from pixels which is fraction of PSF size. The pixel acts as a spatial filter which mitigate the effect of wavefront aberration
  - Signal level drops because WF aberrations causes larger PSF
- DFS signals from multiple rows of pixels can be used to average out the effect of WF aberrations



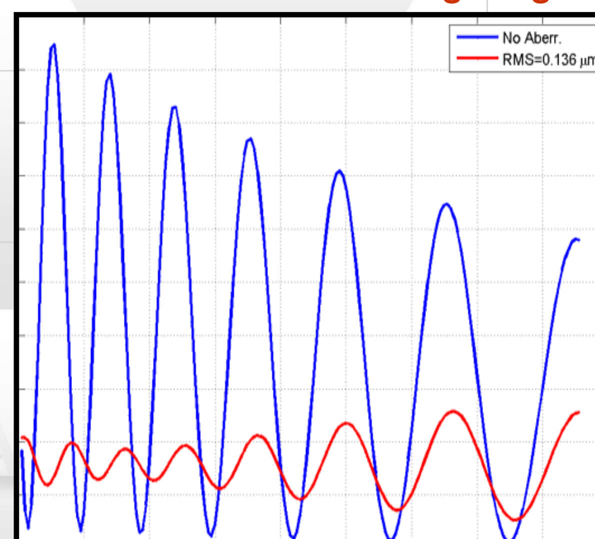
Pixel acts as a spatial filter

DFS Fringe Images Comparison





Ideal and Aberrated Fringe Signal



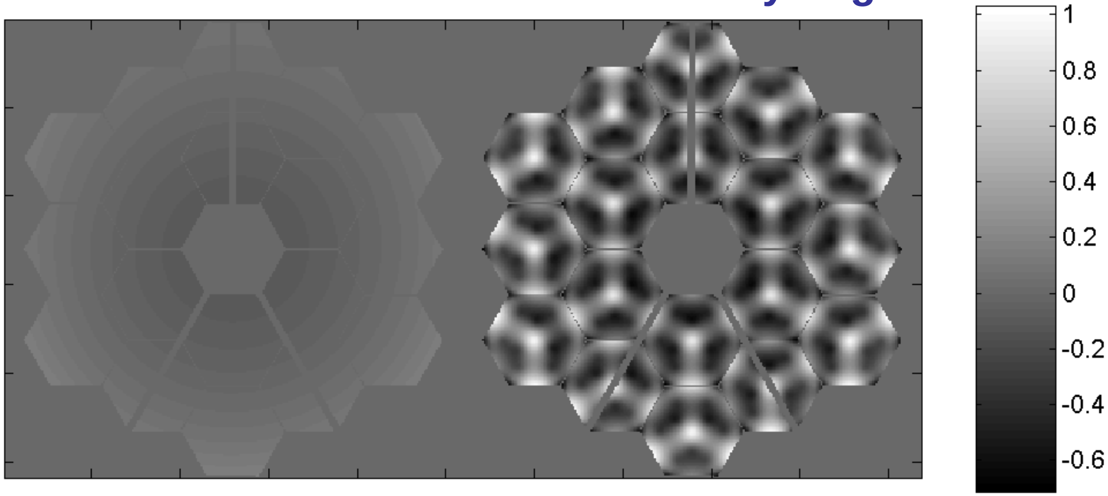
JWST DHS Performance Under Wavefront Aberrations

- **JWST has 18 segments in hexagonal layout and it uses a Dispersed Hartmann Sensor (DHS) for segment mirror coarse phasing**
  - DHS is a dispersed fringe sensor based device which can simultaneously form dispersed fringes from 10 segment edges in a single image
  - Two DHS devices in the NIRCam pupil wheel will measure 20 inter-segment edge heights
  - From the 20 intersegment edge heights measurements, one can reconstruct the 18 segment commands to coarse phase the segmented primary mirror
- **JWST mirror gravity sag during ground Integration and Test (I&T) is used as the wavefront aberration template to study the DHS performance under wavefront Aberration**
- **Modeling the JWST coarse phasing with DHS during JWST ground Integration and Test (I&T)**
  - MACOS model of JWST in I&T configuration
    - The model includes the prescriptions NIRCam optics
    - JWST is in I&T configuration, i.e. double-pass with an auto-collimate flat (ACF)
  - Deformation from gravity sag are applied to the JWST segment mirror and the center of curvature actuators are used to compensate the gravity sag. The residual wavefront error is used in our study
  - Simplifications for quick modeling results
    - Select two out of ten fringes for each DHS are modeled and their performance studied
      - The selected two fringes represent the two types of DHS subapertures
    - Results should applied to other DHS fringes

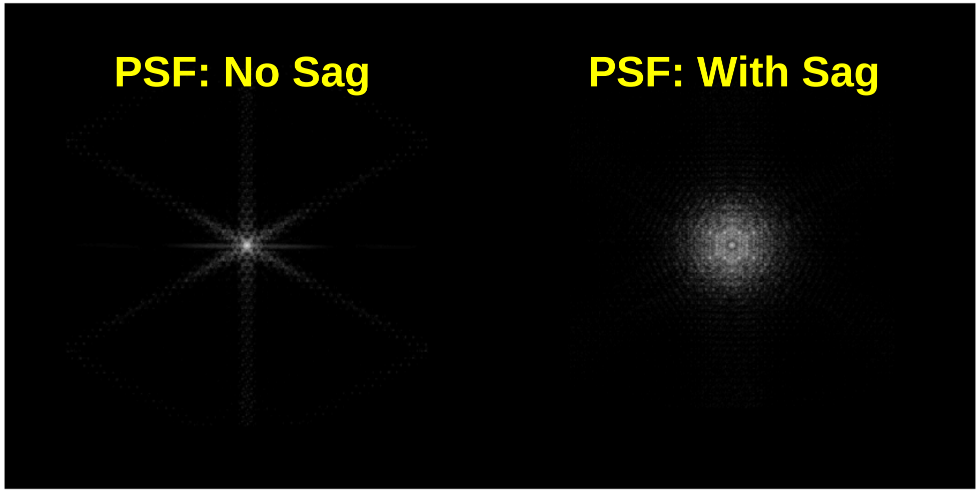
Effect of WF Due to the Gravity Sag During JWST I&T

- For each segment the gravity sag has been compensated with the center-of-curvature correction
- The wavefront is after the double-pass configuration of JWST ground test
- Without Gravity Sag (*left*)
  - RMS WF = 0.058 μm
  - P-V WF = 0.272 μm
- With Gravity Sag (*right*)
  - RMS WF = 0.315 μm
  - P-V WF = 1.741 μm

JWST OPD: with and without Gravity Sag



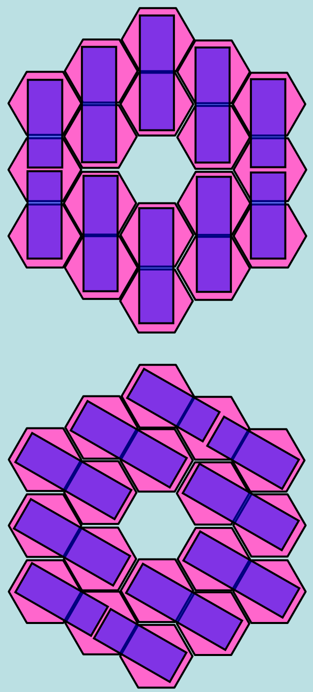
JWST PSF: with and without Gravity Sag

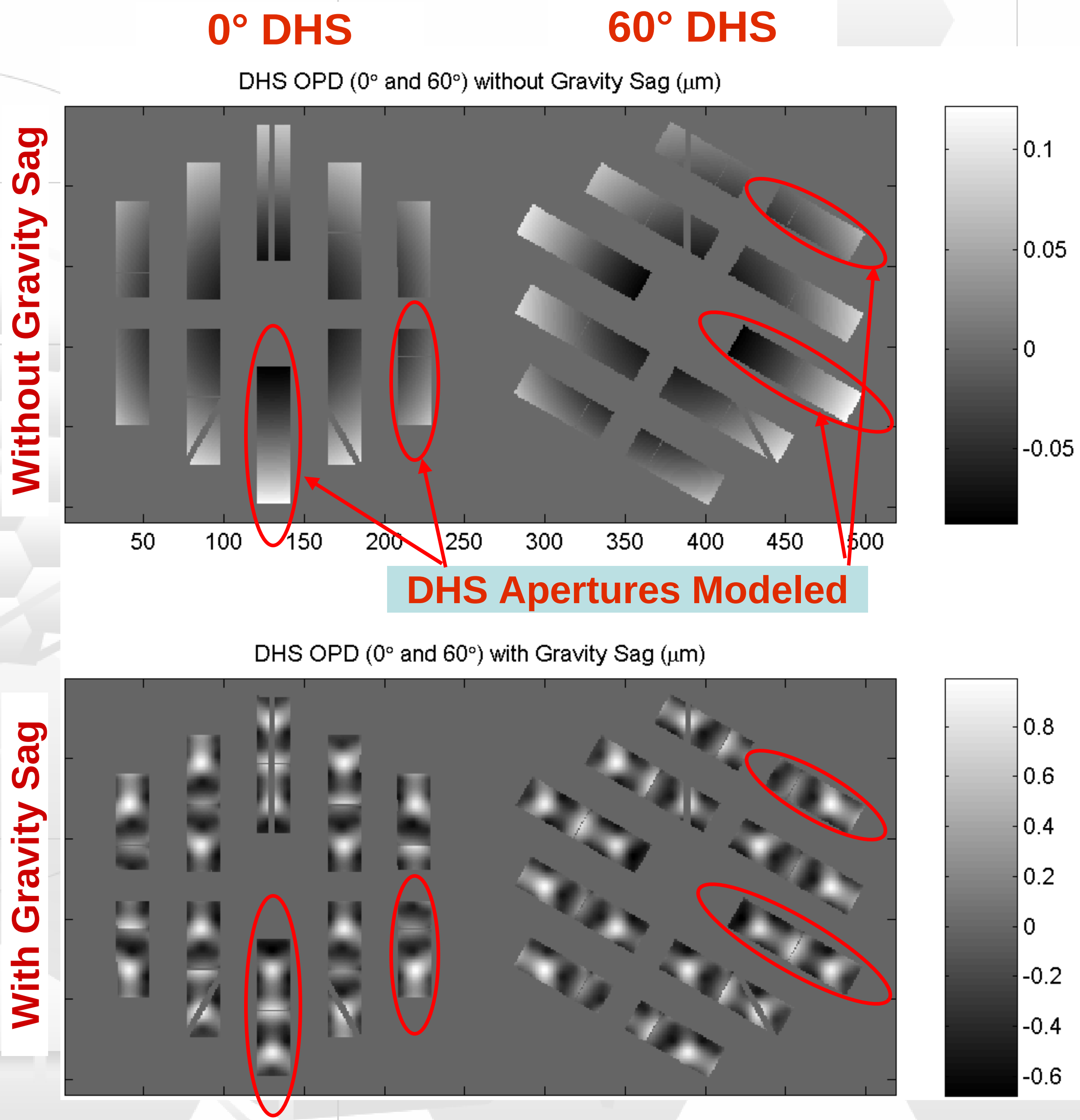


Wavefront of JWST DHS: 0° and 60 ° Dispersion Devices

- DHS subapertures only see part of the overall WF aberration
- Part of WF aberration will be detected as the segment pistons

JWST DHS Concept





DHS Wavefronts and PSFs for the Selected DHS Apertures

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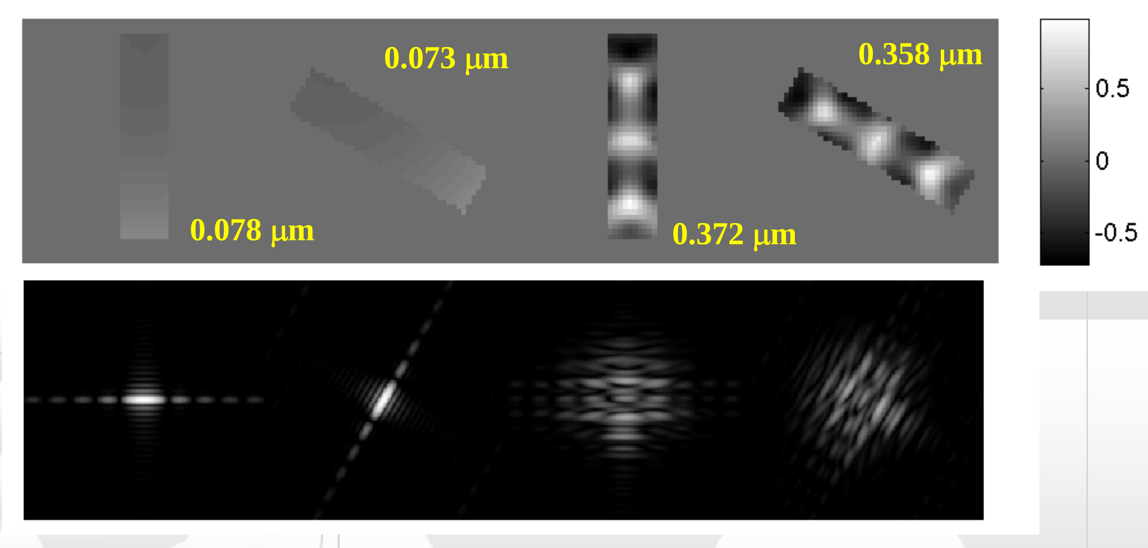
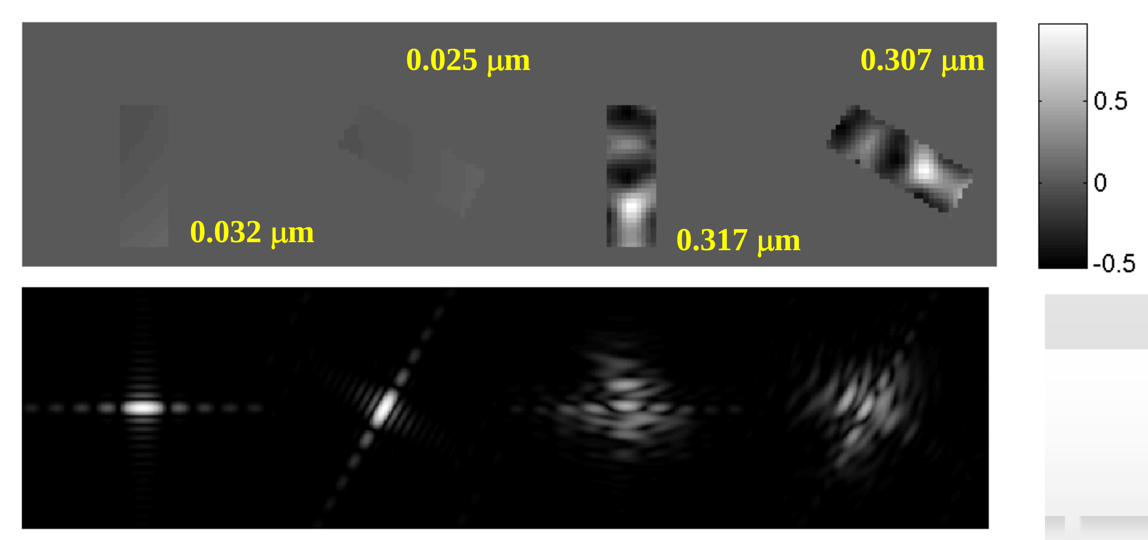
- Two DHS sub-apertures of DHS are selected for modeling for each DHS orientations
  - One with equal area and another with unequal area between two segments
- Sample PSFs and wavefronts with and without gravity sag are shown
- RMS wavefront is labeled on each DHS subaperture
  - Large sub: P-V ~ 1.6 μm
  - Small sub: P-V ~ 1.4 μm
- PSF is log stretched and wavefront is linearly stretched in the same scale
- Due to the nature of the WF formed by the compensated gravity sag the PSF breaks up across the dispersion, forming a multi-strand fringe

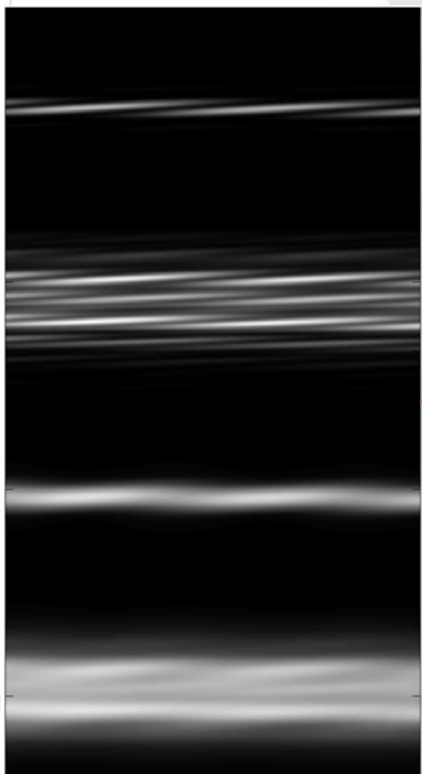




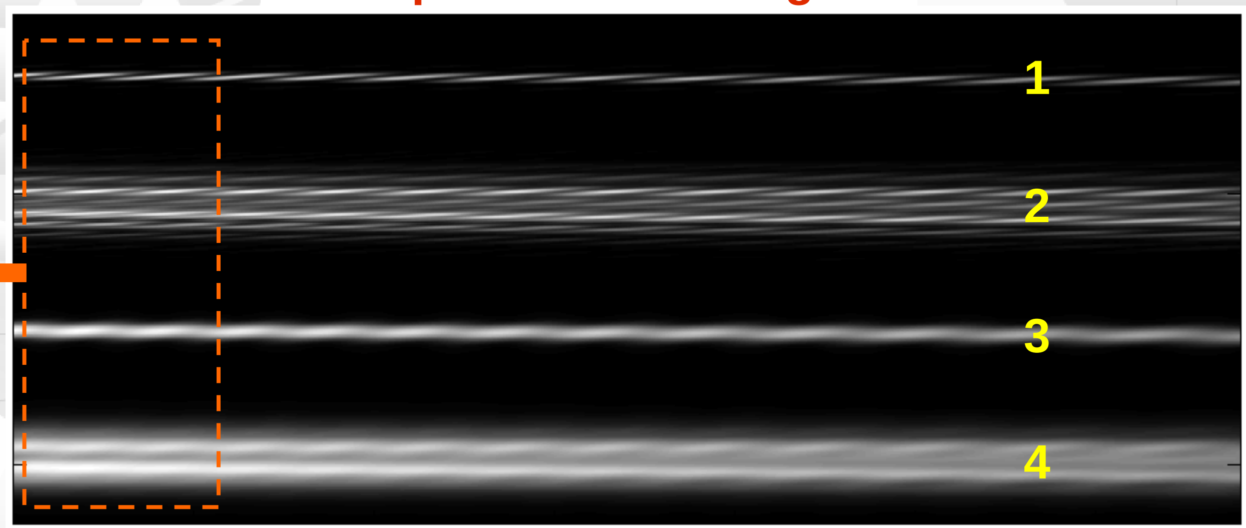
Modeled JWST DHS Fringes with Gravity Sag and Jitter

- Example of DHS fringe from a full subaperture in the 0° DHS. From top to bottom the fringes are
  1. Fringe without gravity sag and without any line-of-sight jitter
  2. Fringe with 1X gravity sag and without line-of-sight jitter
  3. Fringe without gravity sag and with ~6 pixel (FWHM) line-of-sight jitter
  4. Fringe with 1X gravity sag and 6 pixel (FWHM) line-of-sight jitter

Zoom-in View



Samples of DHS Fringes



JWST DHS Performance with Wavefront Aberration

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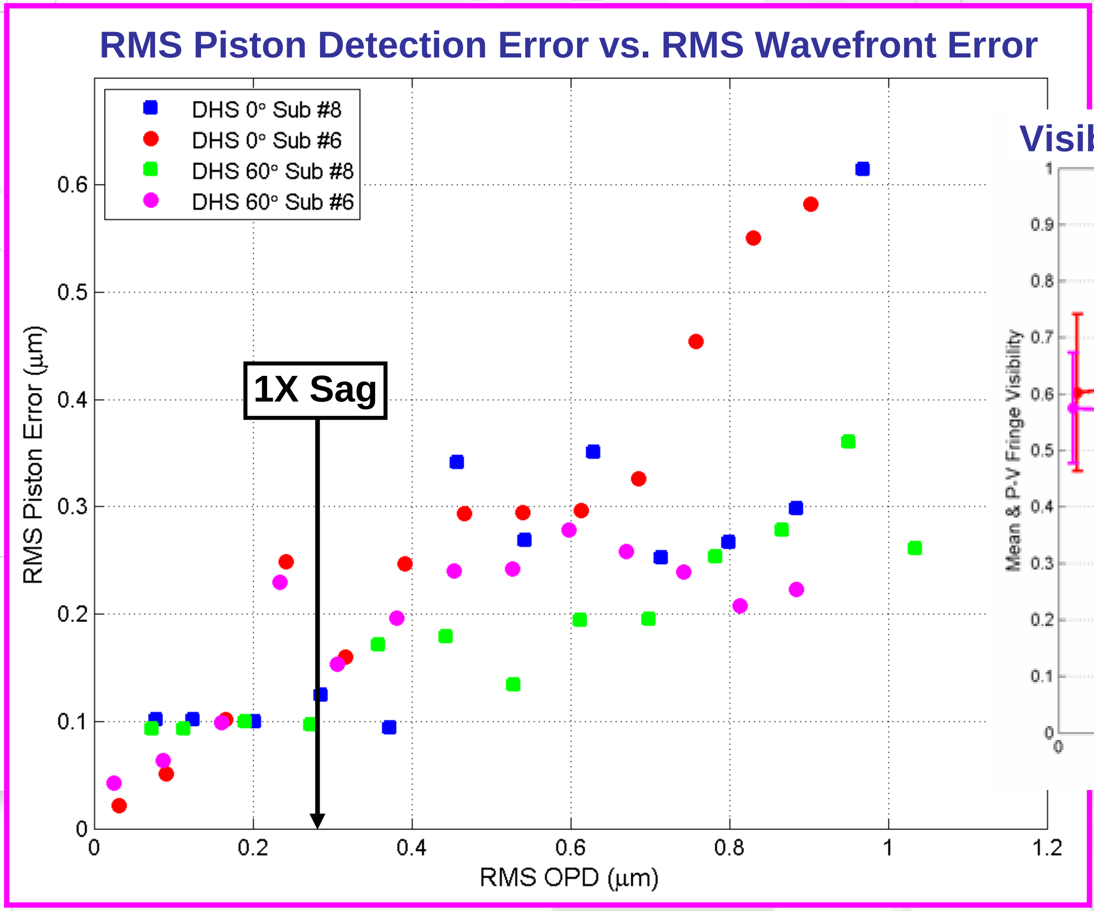
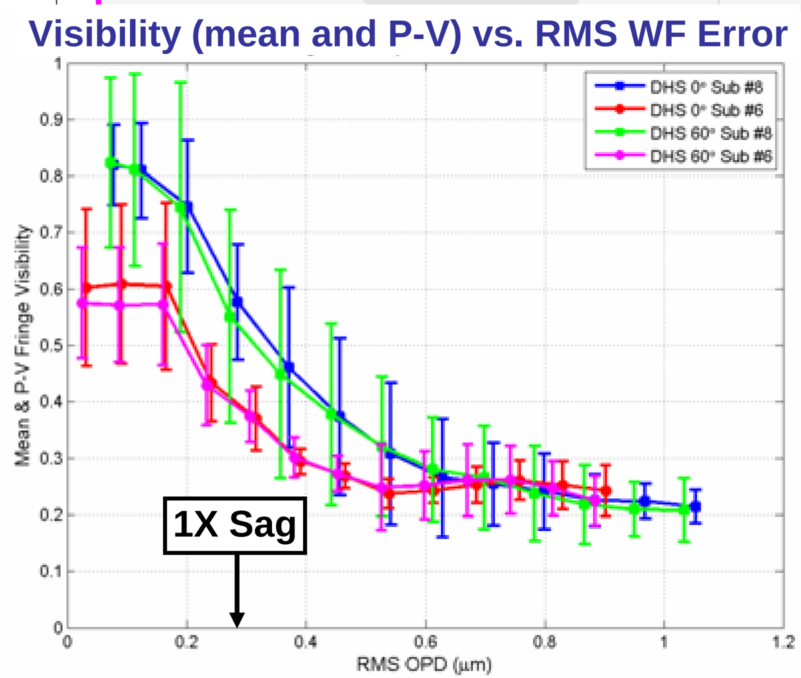
- Wavefront aberration from gravity sag is proportionally scaled to simulate various wavefront error levels
  - Scale factor from 0.25X to 3.0X that of the nominal value of gravity sag are modeled
- Segments are randomly pistoned and DHS fringes are generated with different level of wavefront errors
  - For each WF level 20 random piston cases are calculated. RMS piston distribution is ~10 μm
- DFS algorithm is used to analyze the fringe and detected segment piston is compared with piston applied
- Piston detection errors increase as wavefront aberration increase and fringe visibility drops





DHS Performance with Line-of-Sight Jitter

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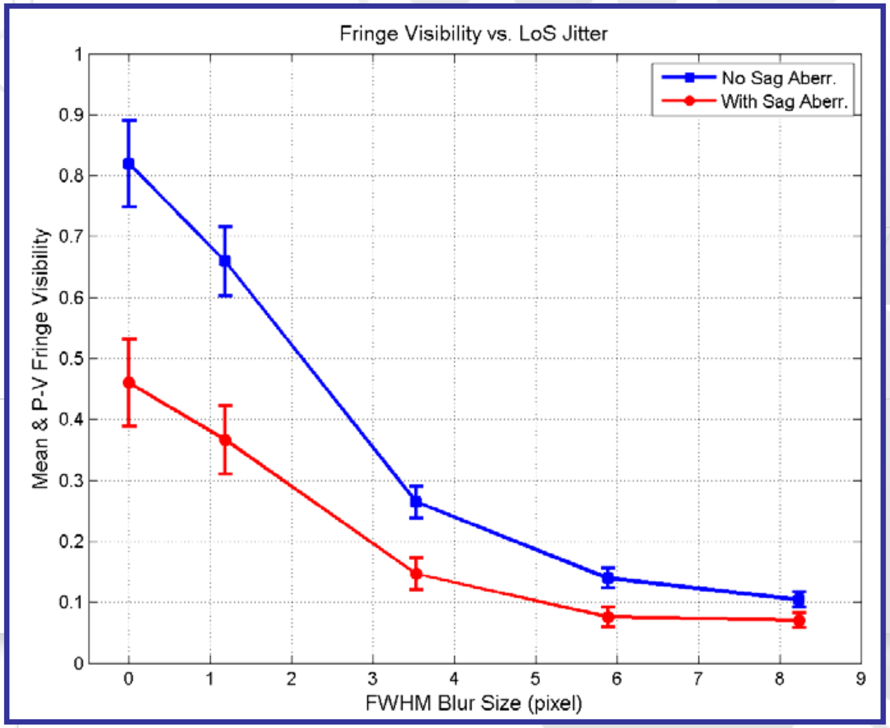
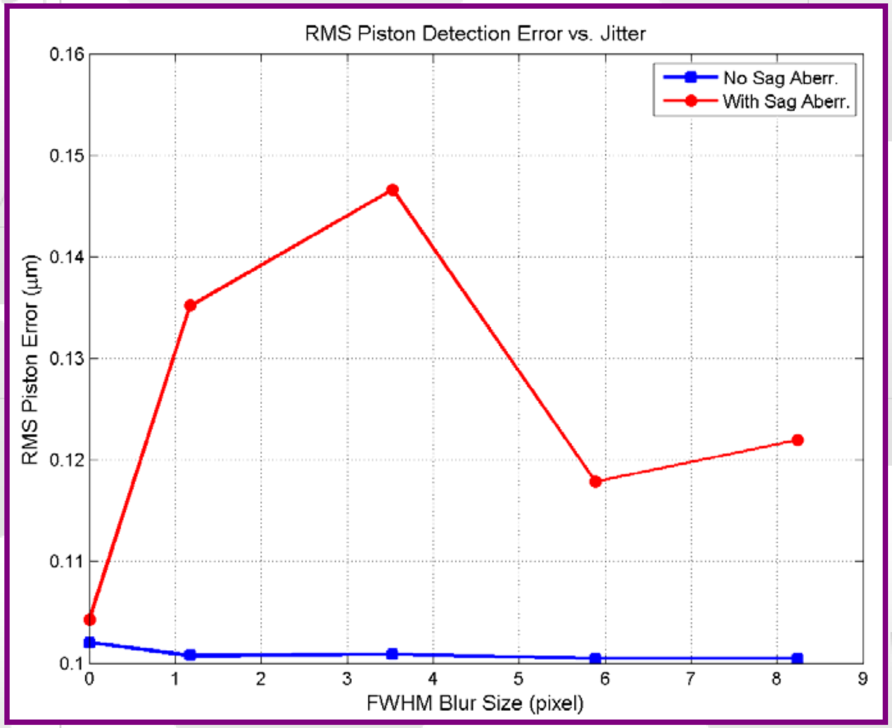
- Telescope line-of-sight jitter is a special kind of aberration. It was simulated by convolving modeled DHS fringes images with a Gaussian blurring kernel
  - The strength of jitter is measured by the equivalent pixel size of full-width-half-max of the blurring kernel
- Segments are randomly pistoned and DHS fringes are generated with two cases of wavefront errors: one without gravity sag and another with 1X gravity sag on the segments
  - For each WF level 20 random piston cases are calculated. RMS piston distribution is ~10 μm
- DFS algorithm is used to analyze the fringe and detected segment piston is compared with piston applied
- While the fringe visibility drops as the blurring increase the piston detection error does not have much correlation with the jitter strength within our test case

Mean & P-V Fringe Visibility vs. LoS Jitter



Piston Detection Error vs. LoS Jitter



Summary

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- Wavefront aberrations will lower the DFS fringe visibility and DFS signal SNR
- The specific effect of wavefront aberration on DFS depends on the aberration type
- Due to the "pixel spatial filter" effect the extracted DFS signal can tolerate moderate amount of wavefront aberrations
- By averaging piston detection results from multiple traces extracted from fringe images DFS can further increase its robustness against wavefront aberration
- Line-of-sight jitter can cause significant loss of fringe visibility will affect more on the aberrated system
- Modeling results have shown that gravity sag on the JWST segment mirror during I&T will lower the DHS fringe visibility by factor of 2–3X and lower the DHS signal intensity by factor of ~5X
  - **Under gravity sag the RMS DHS detection error ~ 100 nm**