Wavefront Sensing and Control

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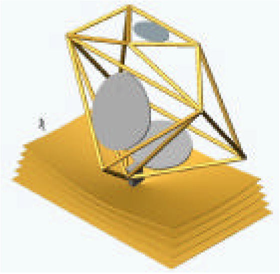
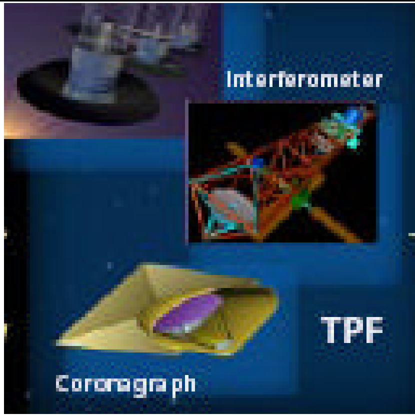
Large Space Telescopes Need WFS&C

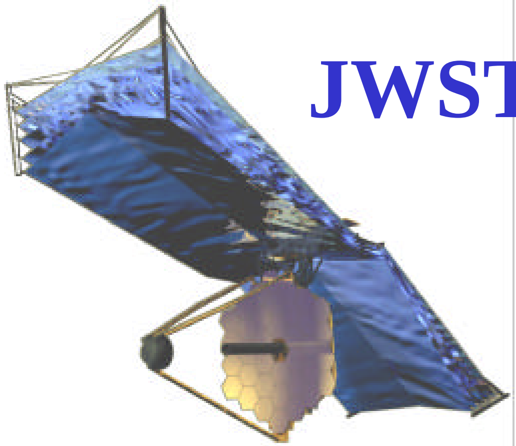
Mission	Aperture (m)	Wavelength	WFS&C WFE	Total WFE	Dynamic range	Spatial resolution	Bandwidth	Tech Freeze date
HST	2.4	UV-IR						
FUSE	0.37	UV						
SIRTF	0.85	IR						
GALEX	0.5	UV						
Kepler	0.95	VIS						
JWST	**6 to 7**	**IR**	**10 nm**	**150 nm**	**1.00E+06**	**5 cyc/ap**	**1.00E-06**	**2004**
Coronagraph precursor	1 to 3	VIS	50 pm	100 pm in band	1.00E+05	30+cyc/ap	1.00E-05	2005?
SIM	0.5	VIS						
TPF Coronagraph	8 to 10	VIS	**40 pm**	50 pm in band	1.00E+06	30+cyc/ap	1e-3 to 1e-6	2008?
TPF IFO	3 to 4	IR	1 nm	10 nm		5-10 cyc/ap		2008?
SAFIR	8 to 10	FIR/SubMM	100 nm?	1 um?	1.00E+05			2011?
Large UV/Opt	big	UV-VIS	1 nm	10 nm	1.00E+06	high	low	2016?
Life Finder	15+	undefined	undefined	undefined	undefined	undefined	undefined	2016?

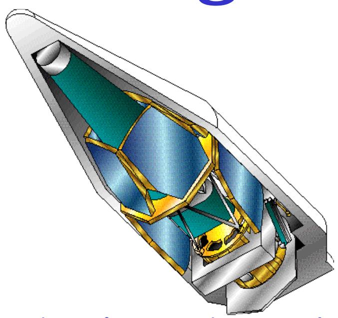


- Future NASA missions promise to open new frontiers in astronomy using large aperture space telescopes
- Getting large apertures into space requires segmenting or folding the primary optic to fit in a booster shroud
- Wavefront control after deployment is required to achieve high optical quality
- JWST mission is pioneering space telescope WFS&C



JWST WF Sensing and Control





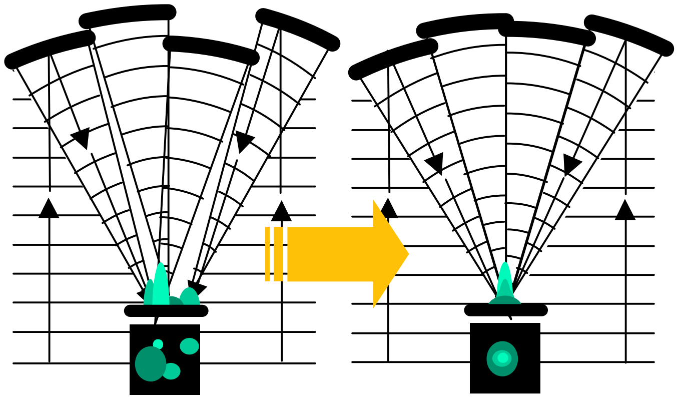
- Primary mirror will be deployed, with from 18 to 36 segments
- Telescope will be cooled to cryo temperatures
- Initial misalignments and figure errors may be large!!!
- WFS&C's job is to align telescope and correct figure errors to achieve diffraction-limited imaging at 2 um wavelength
- We do this with actuators that move and deform the segments
- WF sensing data is provided by science camera images and spectra, which are processed on the ground to determine actuator commands
- JWST will be very stable, by virtue of its environment and design
- Actuators will be off during observations
- Periodic WFS&C updates will keep performance in spec

WFS&C Modes

	NGST Performance Expected		Demonstrated in the Lab	
Control Mode	**Capture Range (peak-valley WFE)**	**Accuracy (rms WFE or WFSE)**	**Capture Range (peak-valley WFE)**	**Accuracy (rms WFE or WFSE)**
Coarse Alignment	**5 mm**	**10 um**	5 mm	10 um
Coarse Phasing	**50 um**	**1 um**	50 um	100 nm
Fine Phasing	**5 um**	**<100 nm**	3 um	20 nm
Actuator Calibration		<10 nm	2 nm	2 nm
Camera-specific WFE Calibration		<10 nm	<10 nm	3.5 nm
PSF Monitoring		<10 nm sensing		6 nm sensing

- The baseline JWST WFC has 3 main initialization modes: Coarse Alignment; Coarse Phasing and Fine Phasing
- Each mode reduces the error it starts with by many times, and then hands over to the succeeding mode
- PSF Monitoring monitors science observations to track the evolving WF error over long periods of time
- Fine Phasing is repeated at intervals (1/month?) throughout the mission

Coarse Alignment - Capture and Tilt

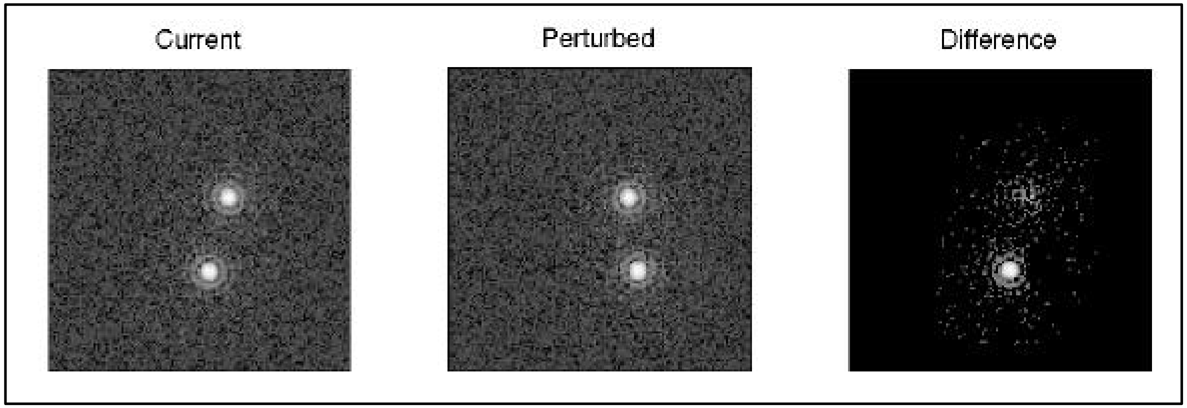


Government Baseline		NGST Performance		Demonstrated in the Lab	
Control Mode	Algorithm	Capture Range (peak-valley WFE)	Accuracy (rms WFE or WFSE)	Capture Range (peak-valley WFE)	Accuracy (rms WFE or WFSE)
Coarse Alignment	**Segment ID**	**5 mm**		5 mm	
	Coarse Align				
	Focus		**10 um**		10 um

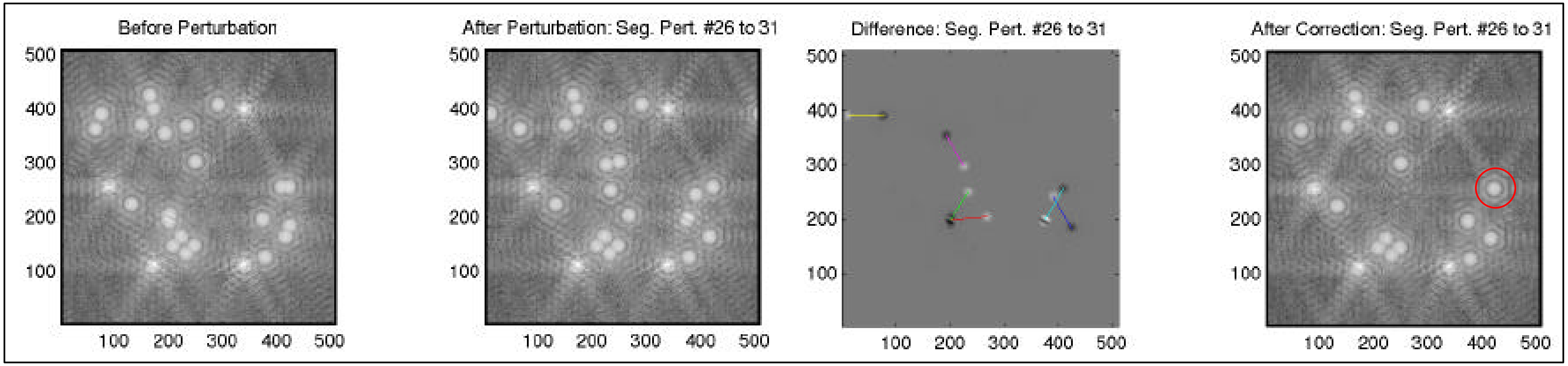
- At first light, the telescope is pointed at a bright, isolated star
- The initial image is broken into many blobs: defocussed, separated segment images
- Segment ID takes an image, moves segments incrementally, takes another image, then “differentiates” the 2 images to identify which blob corresponds to which segment
- Missing spots trigger a larger segment scan, stepping segment tilts in units of the camera field of view, until that segment is found
- Once identified, segment spots are placed in particular positions on the detector for Focus

Coarse Align Image Differentiation Examples

- Small tilts Dx_i and Dy_i are introduced between exposures (here i is the ith segment)
- The difference frame is $DI_i = pos|I_i(x_i, y_i) - I_i(x_i+Dx_i, y_i+Dy_i)|$

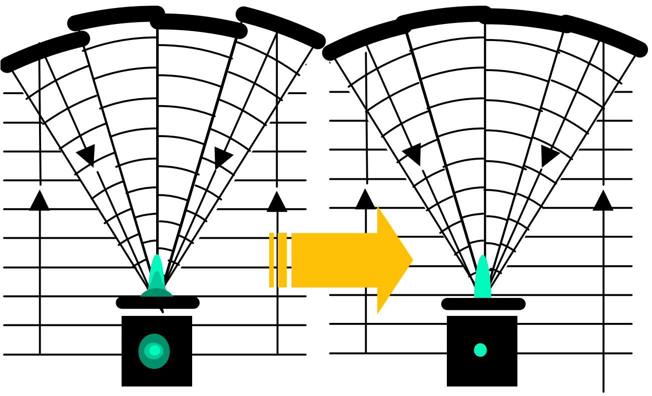


Example from WCT-2 testbed. Difference shows the location of the segment blob.



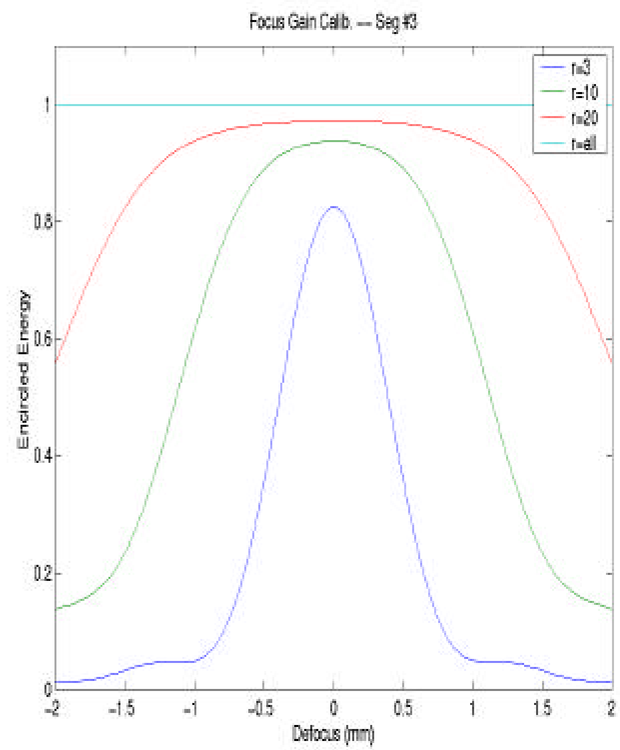
Example using JWST simulation with large number of segments. 6 segments are identified simultaneously, and moved to overlie at the reference location.

Coarse Alignment - Focus

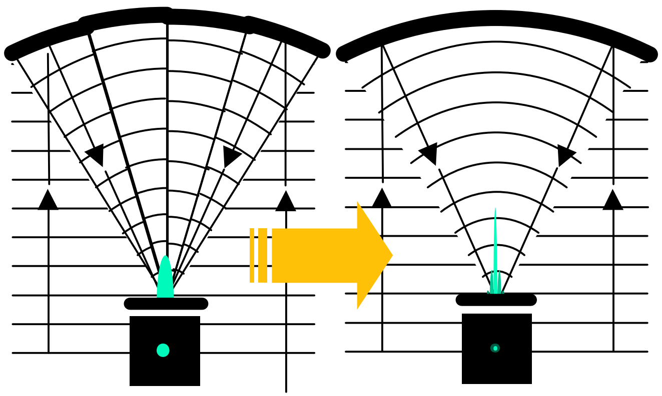


Government Baseline		NGST Performance		Demonstrated in the Lab	
Control Mode	Algorithm	Capture Range (peak-valley WFE)	Accuracy (rms WFE or WFSE)	Capture Range (peak-valley WFE)	Accuracy (rms WFE or WFSE)
Coarse Alignment	Segment ID	5 mm		5 mm	
	Coarse Align				
	Focus		10 um		10 um

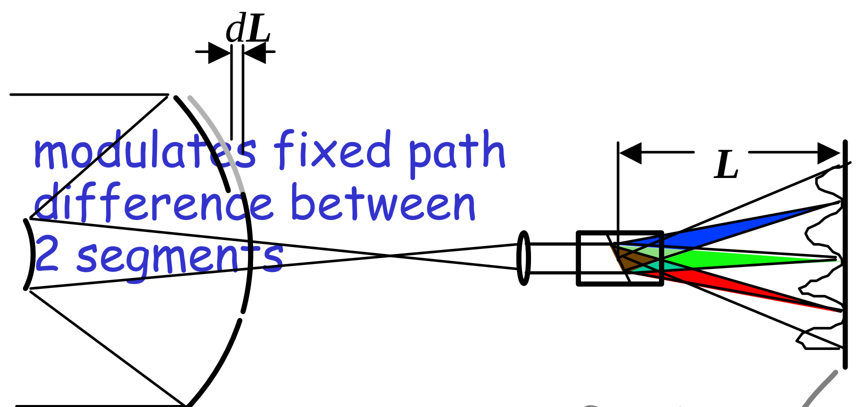
- Each segment is focused by driving it in piston to minimize a 3-stage encircled-energy metric
- When defocus is large, steps are computed using geometric optics, and convergence is rapid
- When near the segment depth of focus, a hill-climbing method is used
- When completed, segments are focused but not coherently phased
  - Piston errors in the 10s of microns

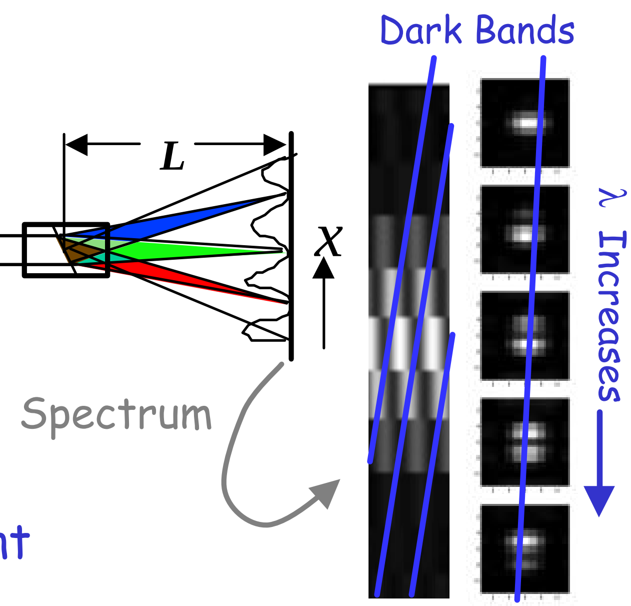


Coarse Phasing - DFS



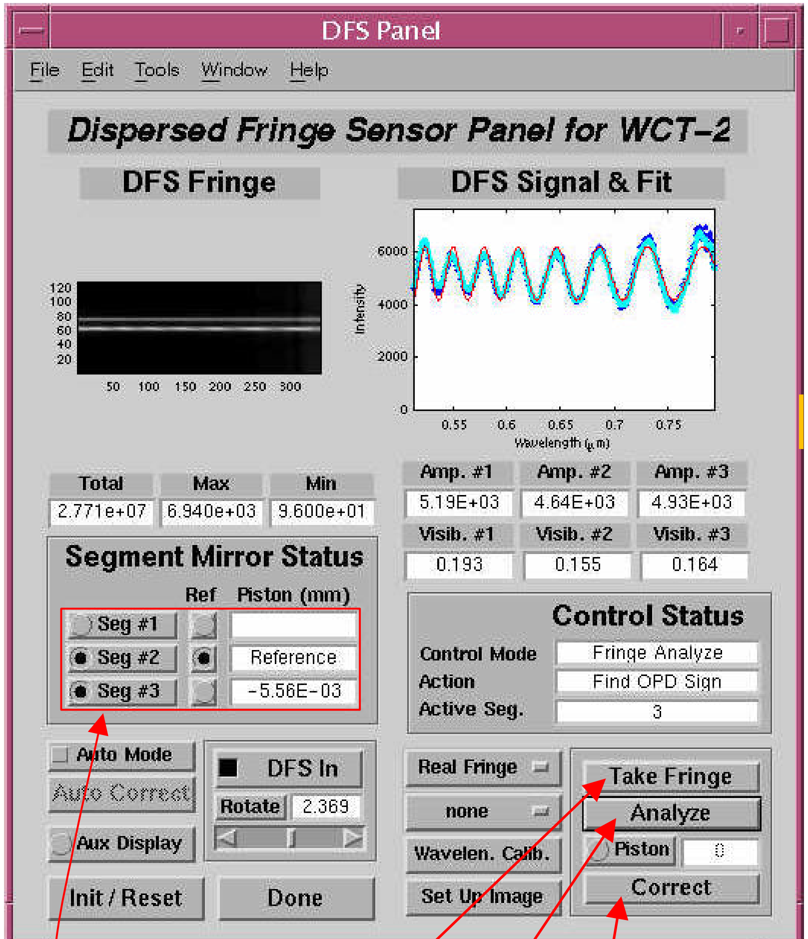
Government Baseline		NGST Performance		Demonstrated in the Lab	
Control Mode	*Algorithm*	Capture Range (peak-valley WFE)	Accuracy (rms WFE or WFSE)	Capture Range (peak-valley WFE)	Accuracy (rms WFE or WFSE)
Coarse Phasing	**Dispersed-Fringe Sensing**	**50 um**	**1 um piston error**	50 um	100 nm piston error
	White-Light Interferometry	10 um	10 nm piston error	5 um	20 nm piston error



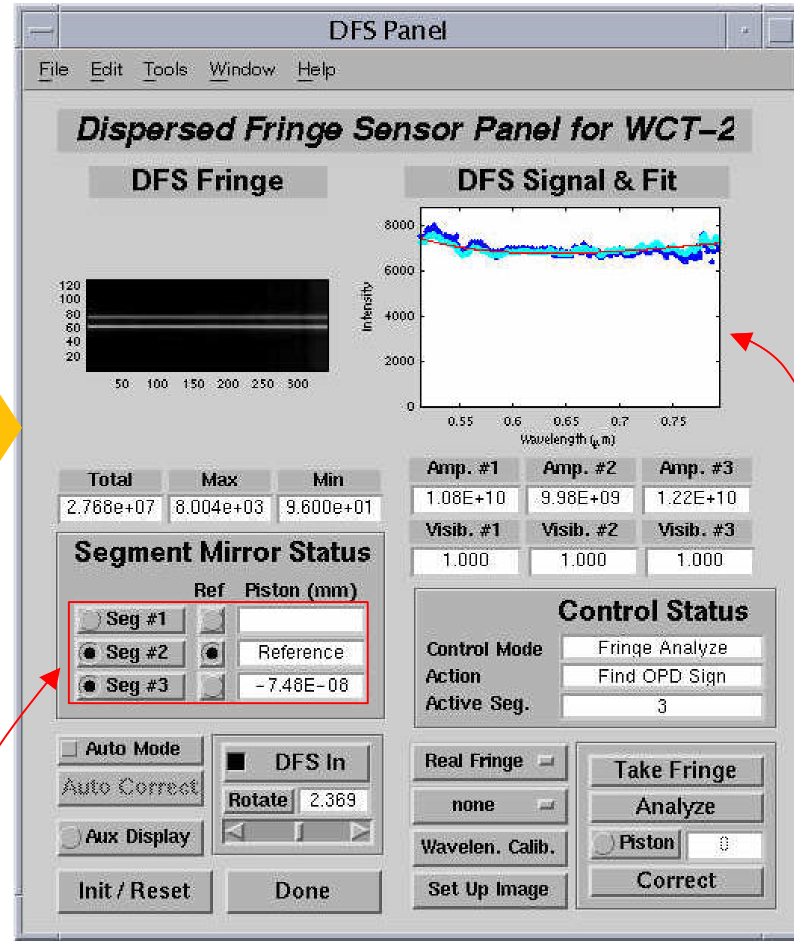


- Wavelength variation modulates fixed path difference between 2 segments
- Bright where λ is coherent with *dL*
- Null where it combines destructively
- Period of fringe gives absolute piston displacement
- Slope of dark bands gives the sign

Coarse Phasing - DFS Example from WCT-2



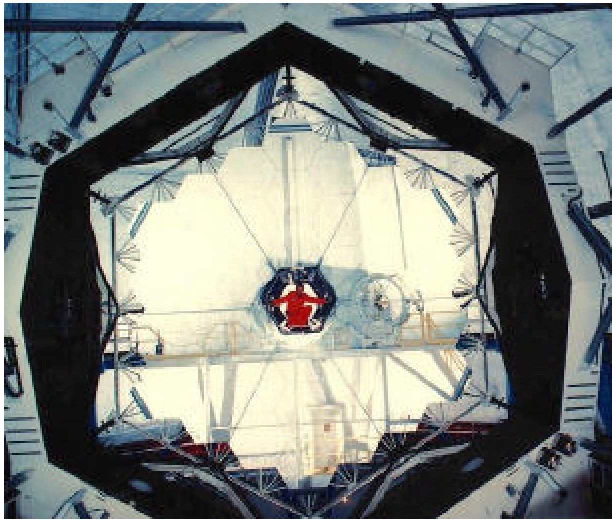
1. Take picture
2. Analyze picture to extract fringe
3. Result
4. Implement correction

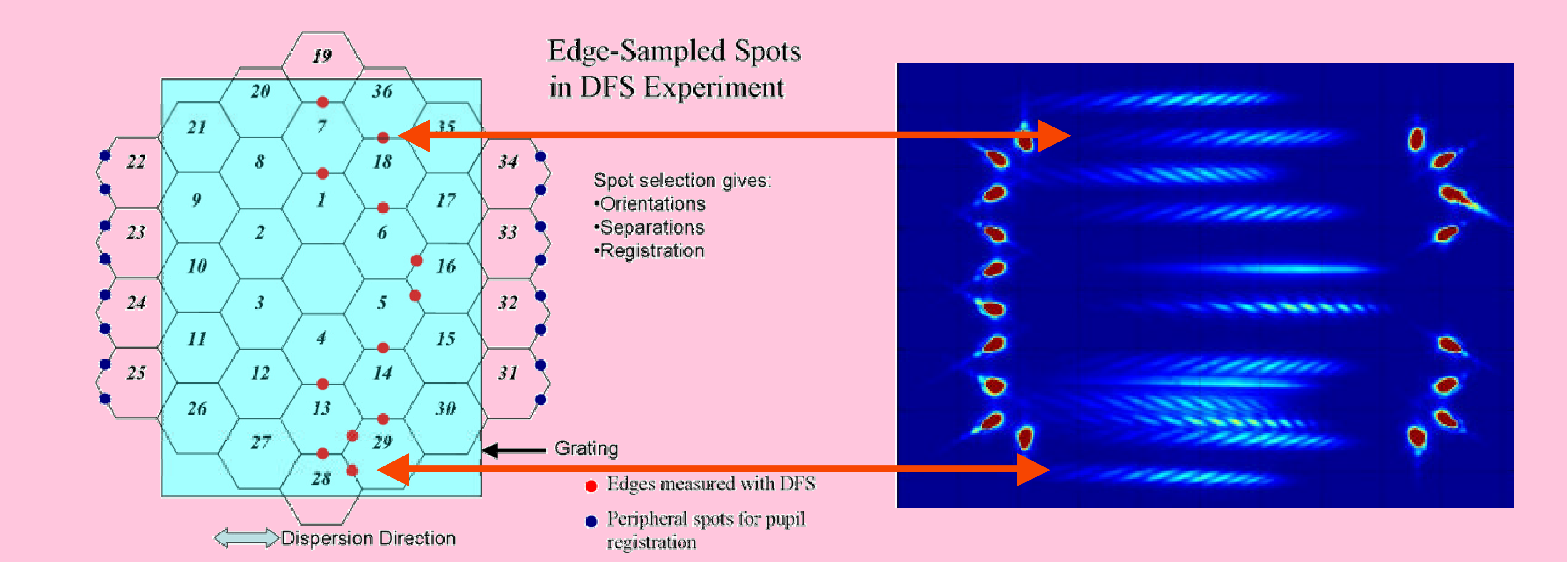


- Post-correction fringe shows very little modulation
- Detected piston reduced to near zero

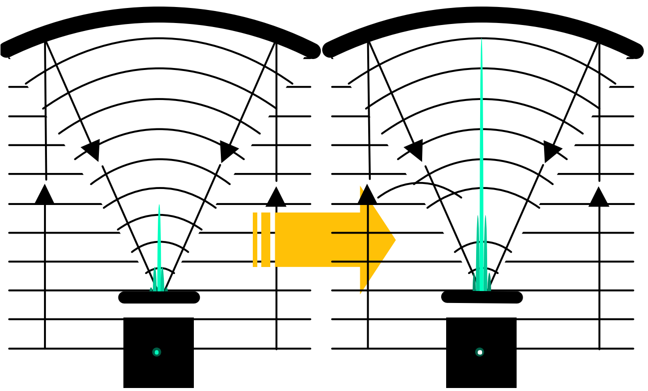
DFS at Keck

- Dispersed Fringe Sensing demonstrated using Keck 2
  - JWST shares Keck Aperture: 36 hexagonal segments
  - DFS piston measurements obtained using a combined DFS + Shack-Hartmann mask covering a subset of edges.
  - DFS results should match piston commands
  - DFS results should also match Keck "Phasing Camera System" (PCS) measurements
    - PCS is, a modified Shack-Hartmann sensor that uses WLI to find edge offsets
- DFS Performance summary (preliminary):
  - Capture range: >30 mm
  - Accuracy: <300 nm





Fine Phasing - WF Sensing

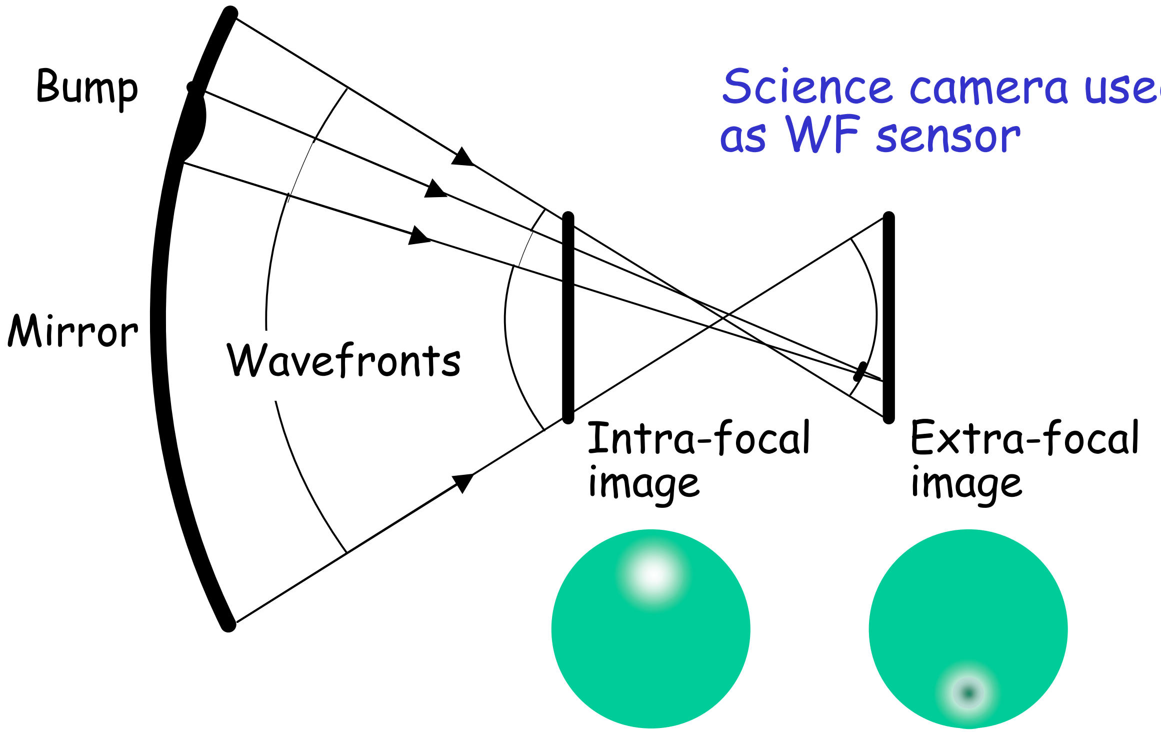


Government Baseline		NGST Performance		Demonstrated in the Lab	
Control Mode	Algorithm	Capture Range (peak-valley WFE)	Accuracy (rms WFE or WFSE)	Capture Range (peak-valley WFE)	Accuracy (rms WFE or WFSE)
Fine Phasing	WFS/MGS	>15 um	<10 nm	>3 um	3.5 nm
	WFC	>15 um	<100 nm	>3 um	20 nm

- Image-based WF sensing has important advantages...

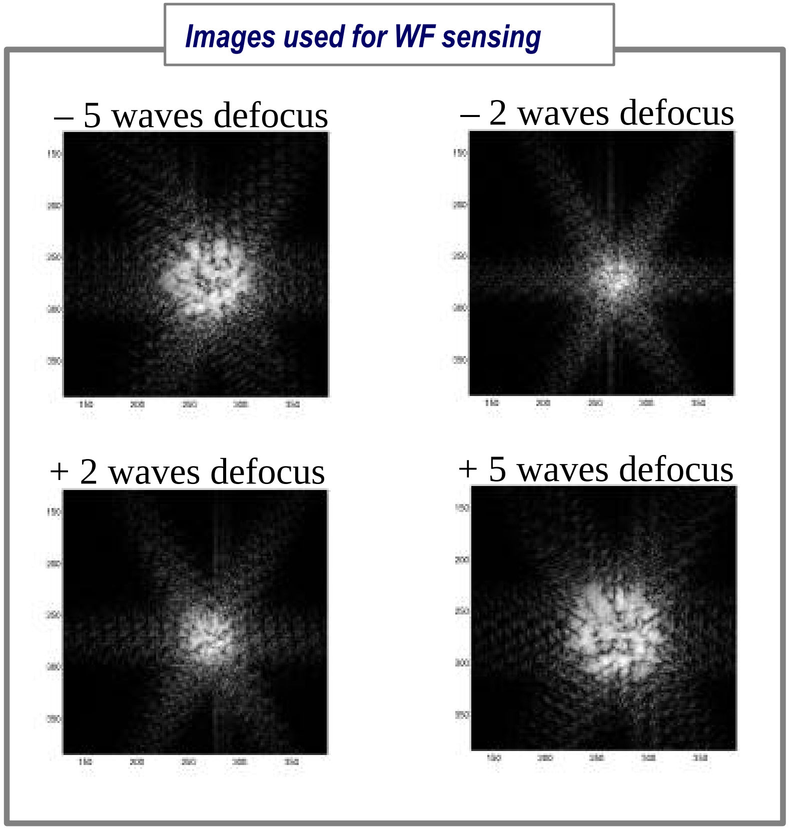
Method	Instrument	Common mode reject	Accuracy	Range	Spatial resolution	Noise & jitter	Resolves piston?
Image-based	Any camera, any field	Yes	Excellent	Med (50 um)	High	Robust	Yes (multi-color)
Hartman sensor	Dedicated or flip-in	No	Good	High (1 mm)	Med	Robust	No
Shearing interf.	Dedicated	No	Good	Med	High	Robust	Maybe
Phase-shifting interf.	Dedicated	No	Excellent	Med	High	Sensitive	Yes (multi-color)

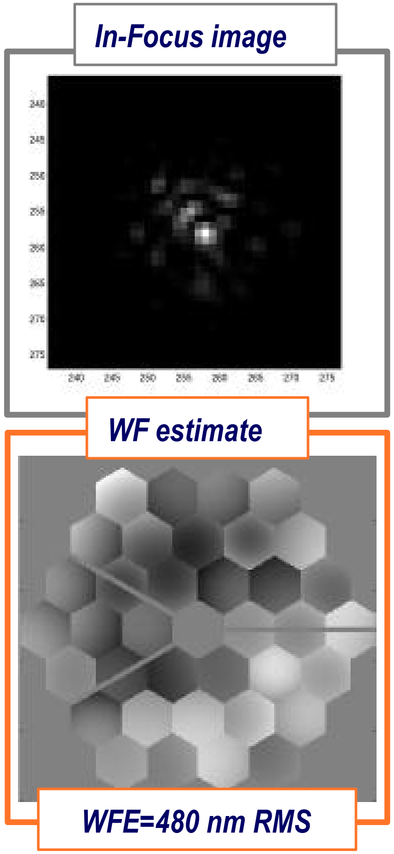
WF Sensing Using Defocussed Images



- 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

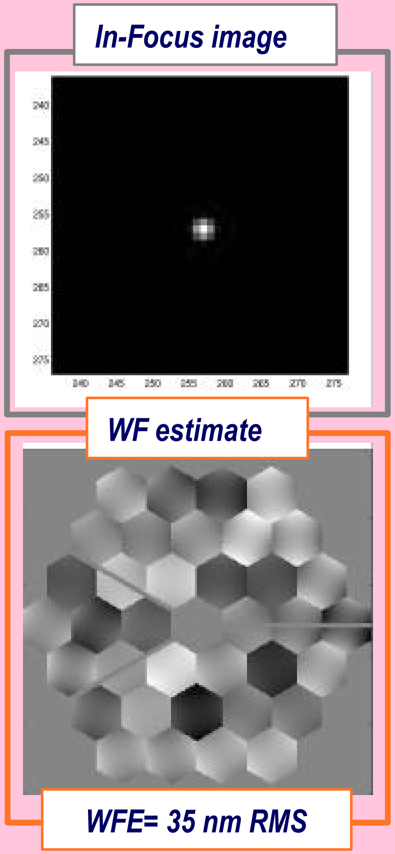
Fine-Phasing JWST in Simulation



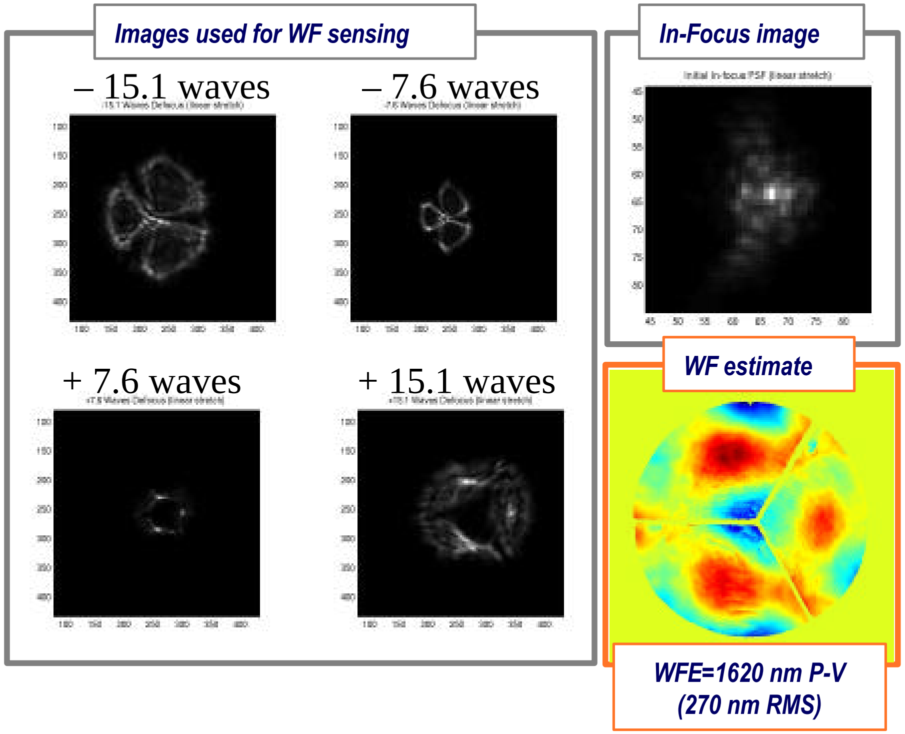


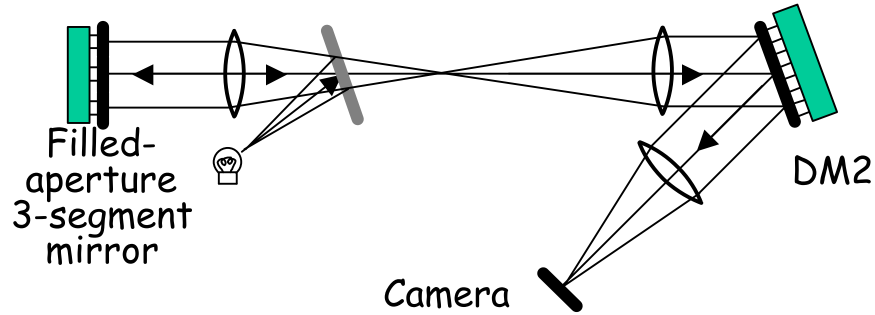
- Fine Phasing uses MGS Phase Retrieval to estimate WF
- WF control is applied using segment RB and RoC actuators

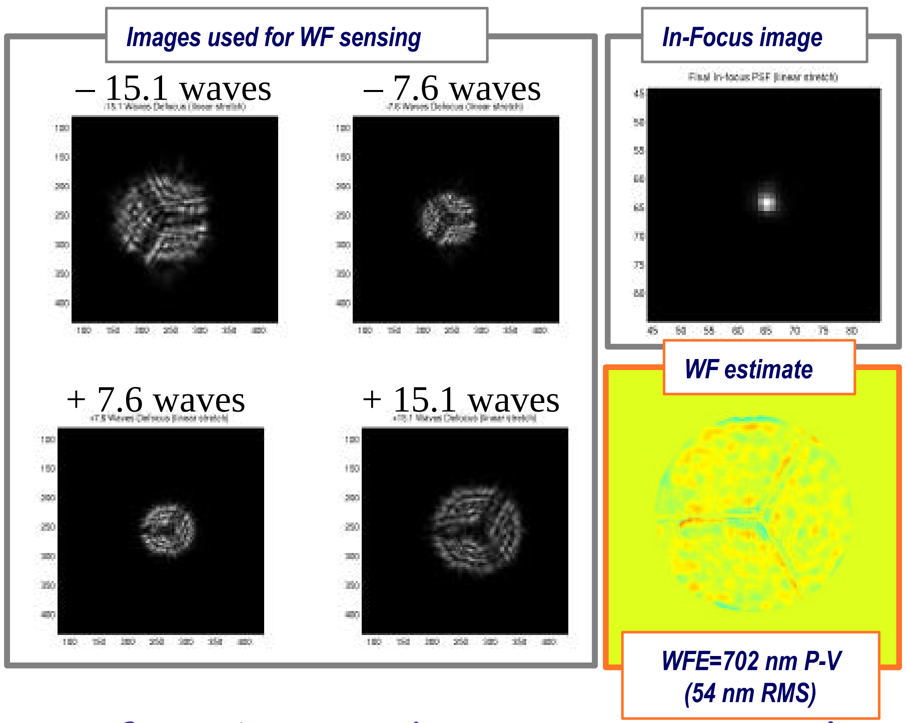
- Post-control WF meets 150 nm objective



Example from WCT-3





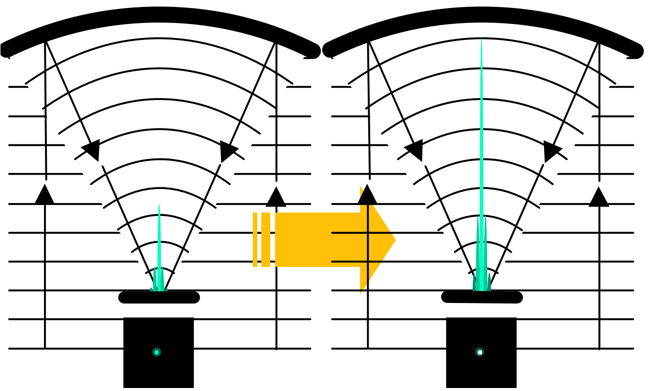


- Experiment here is to correct segment aberrations
  - Initial WFE 1620 nm peak-to-valley, 270 nm RMS…

- After DM and segment control

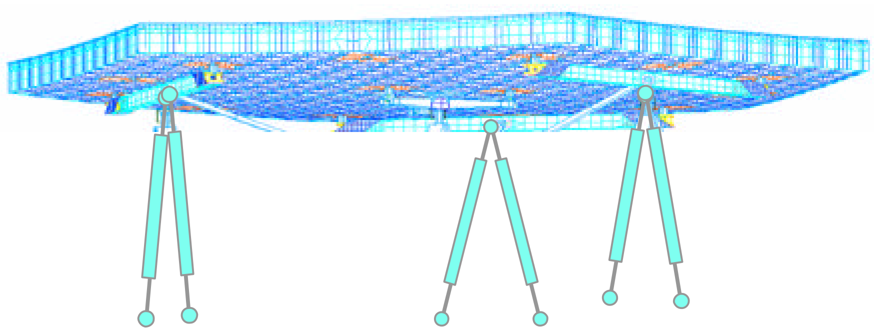
  …reduced to 54 nm RMS

Fine Phasing - WF Control

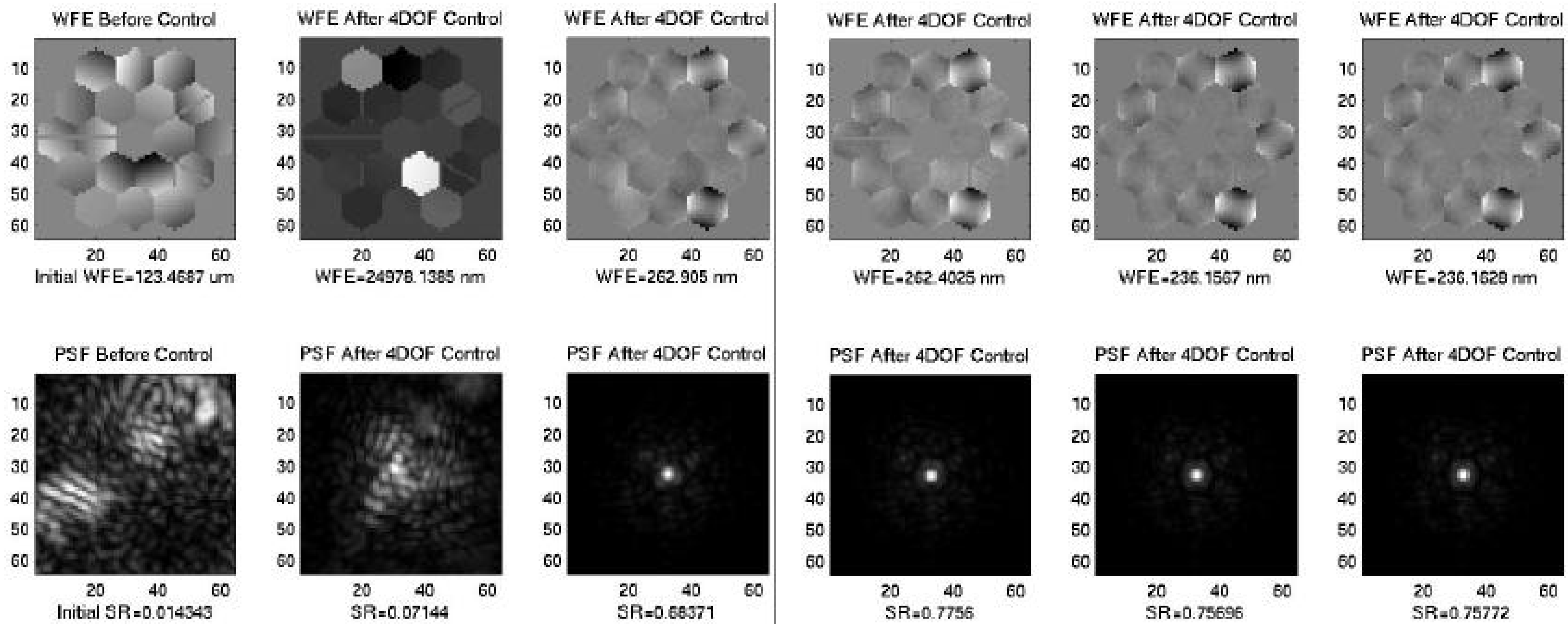


Government Baseline		NGST Performance		Demonstrated in the Lab	
Control Mode	Algorithm	Capture Range (peak-valley WFE)	Accuracy (rms WFE or WFSE)	Capture Range (peak-valley WFE)	Accuracy (rms WFE or WFSE)
Fine Phasing	WFS/MGS	>15 um	<10 nm	>3 um	3.5 nm
	WFC	>15 um	<100 nm	>3 um	20 nm

- WF control is effected using actuators to move segments in 6DOF and to change segment RoC
- 2-stage linear actuators grouped into 3 bipods move segments in tip, tilt, twist, decenter (X and Y) and piston
  - Coarse stage provides long stroke, looser accuracy
  - Fine stage provides short stroke, finer precision

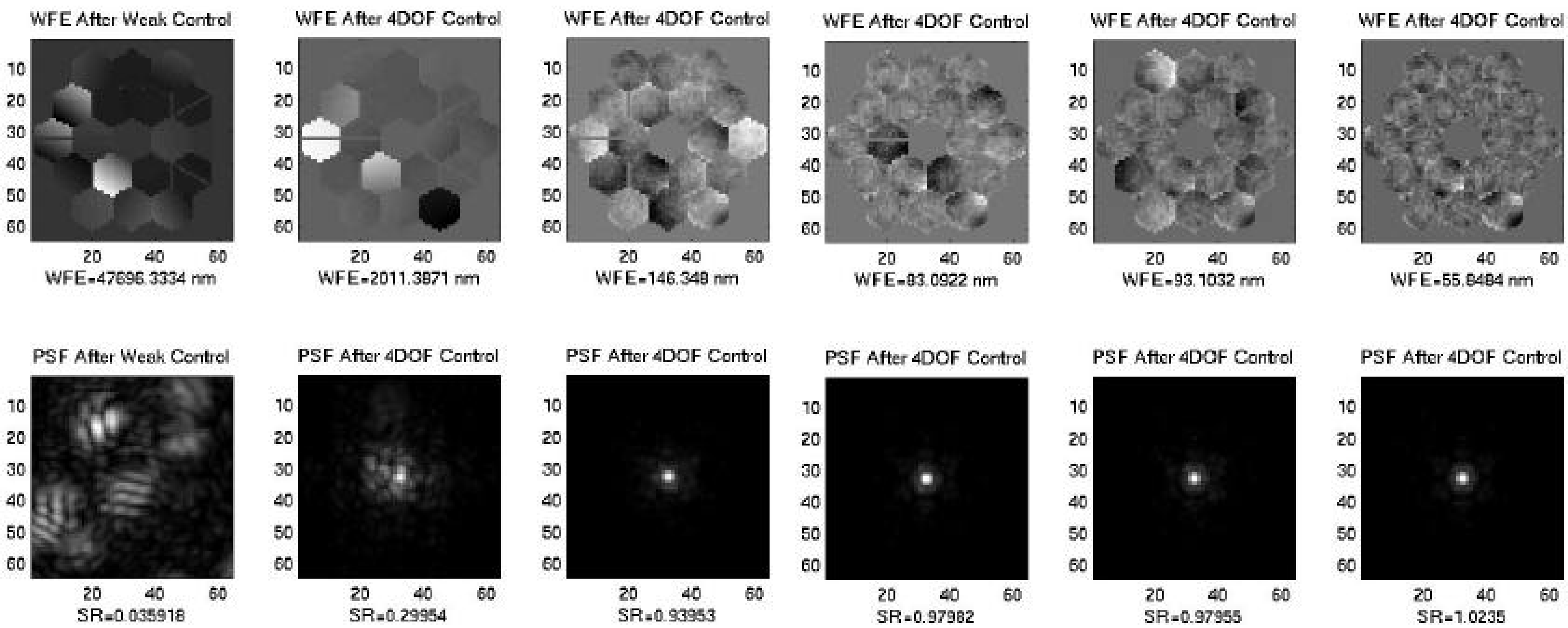


WF Control with Hexapods Example



- Fine Phasing (WFS and WFC) initiated with large errors in all rigid-body and RoC DOFs
- Stroke-dependent actuation error
  - Large actuator stroke leaves large actuation error
  - Subsequent smaller actuator commands leave less actuation error
  - 3-4 iterations are necessary to reduce actuator error to smallest level, corresponding to minimum error (3 nm)

Example (cont.)

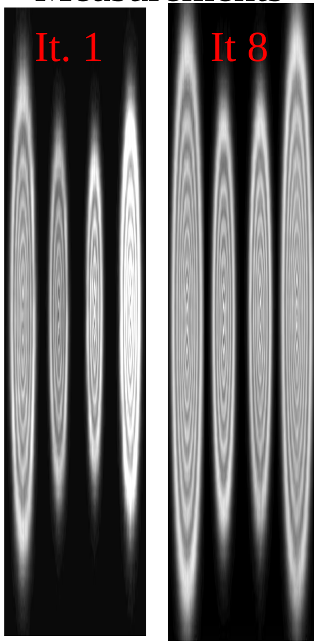


- "Weak" DOFs (decenter and twist) are controlled
  - Weak influence of these DOFs means large motions are necessary to compensate small aberrations
  - Large actuator movements leave large actuation errors in 4 strong DOFs
- *A 2nd round of 4DOF control cleans up actuation errors and control nonlinearities*

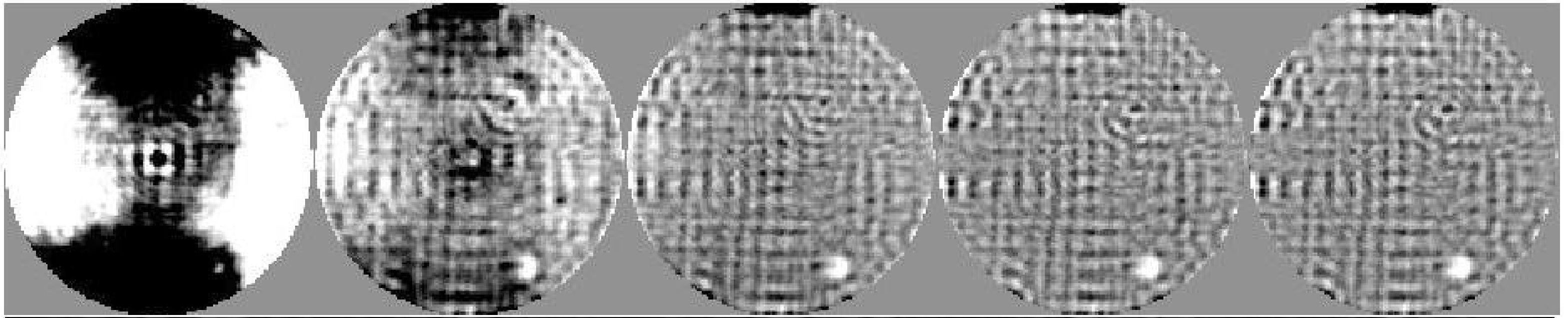
High Contrast Imaging Testbed

- The TPF HCIT is intended to demonstrate extremely high contrast coronagraphy for planet hunting
- Requires suppressing scattered light in low and mid spatial frequencies using (in this example) a 32^2 actuator DM
- This chart shows a sequence of WFS&C iterations leading to a WF corrected to $\lambda/5000$ for spatial frequencies within the DM bandpass

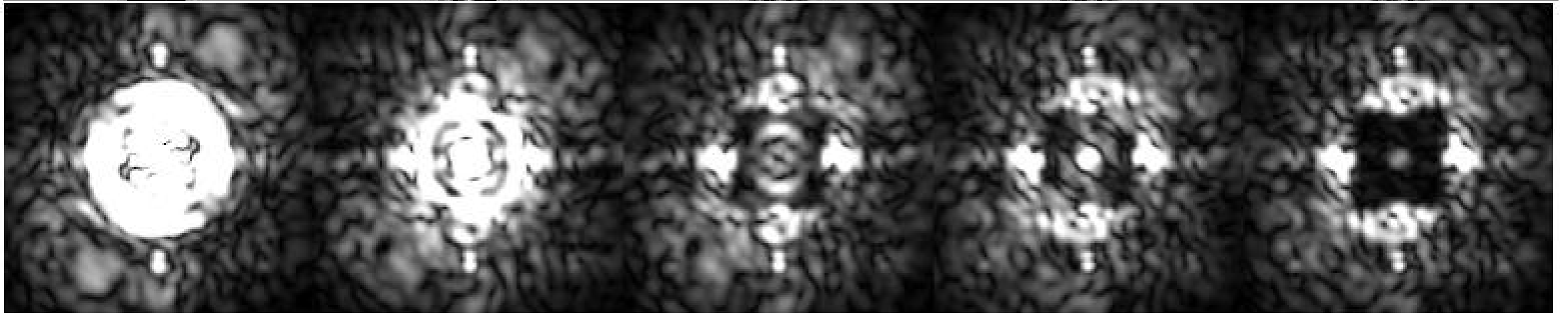
Focus-Diverse Measurements



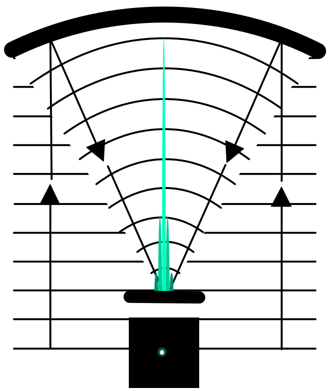
Sequence of Wavefront Estimates



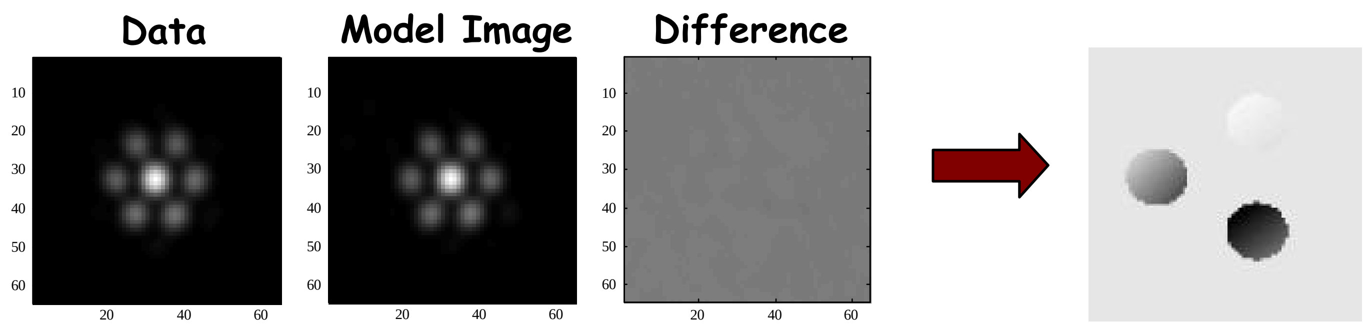
Sequence of WFE Power Spectral Densities



PSF Monitoring



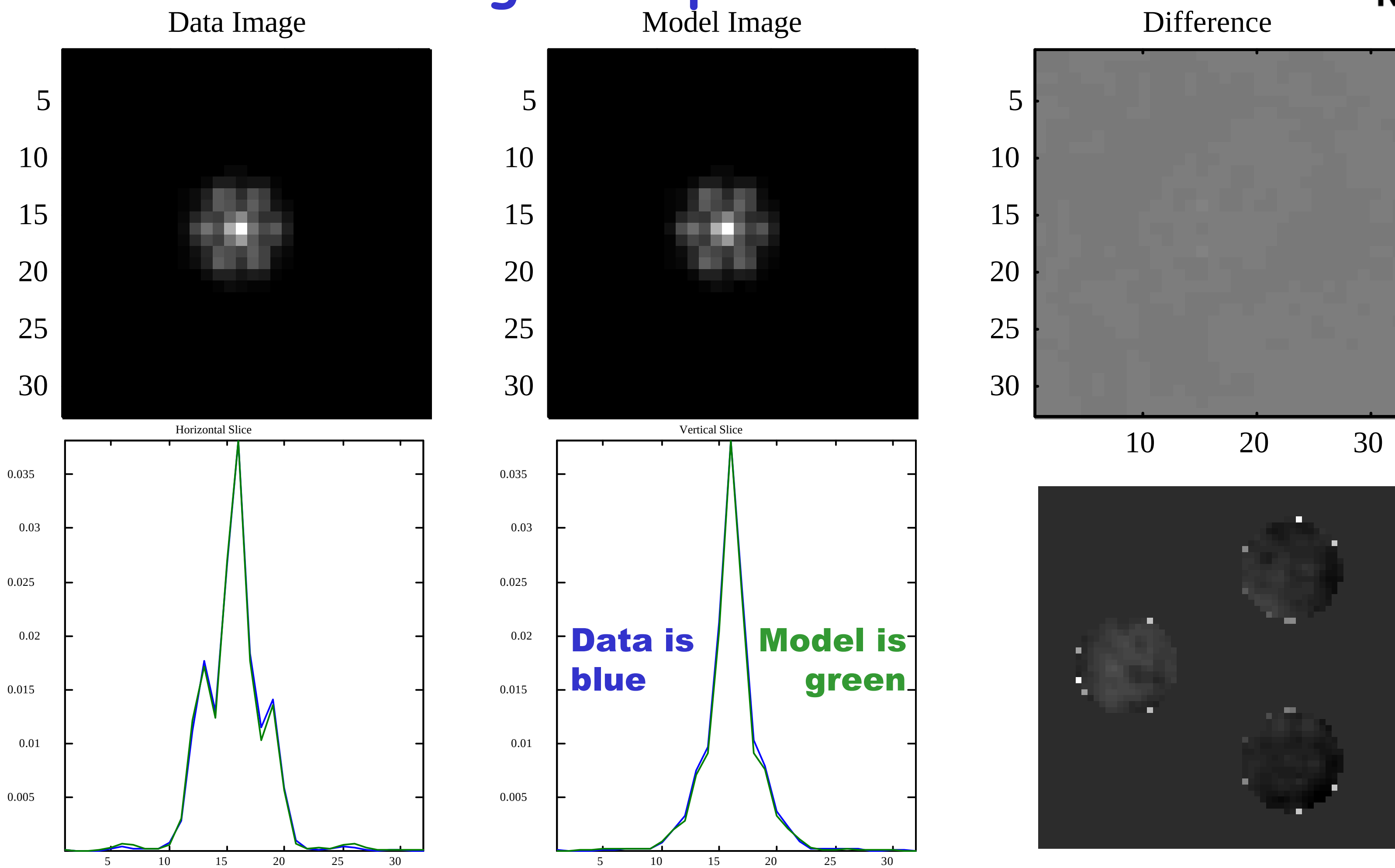
Government Baseline		NGST Performance		Demonstrated in the Lab	
Control Mode	Algorithm	Capture Range (peak-valley WFE)	Accuracy (rms WFE or WFSE)	Capture Range (peak-valley WFE)	Accuracy (rms WFE or WFSE)
PSF Monitoring	**IPO/ Prescription Retrieval**		<10 nm		6 nm
Fine Phasing	WFS/MGS	>15 um	<10 nm	3 um	3.5 nm
	WFC	>15 um	<100 nm	3 um	20 nm



Retrieved Segment Aberrations

- In-focus PSF Optimizer (IPO) measures low spatial-*f* components of WFE from narrow-band in-focus images
  - IPO uses Prescription Retrieval model-matching algorithm
- IPO provides robust, accurate control for WCT-2
- IPO images can be taken from the science data stream: a near-zero overhead means of monitoring the evolving WFE

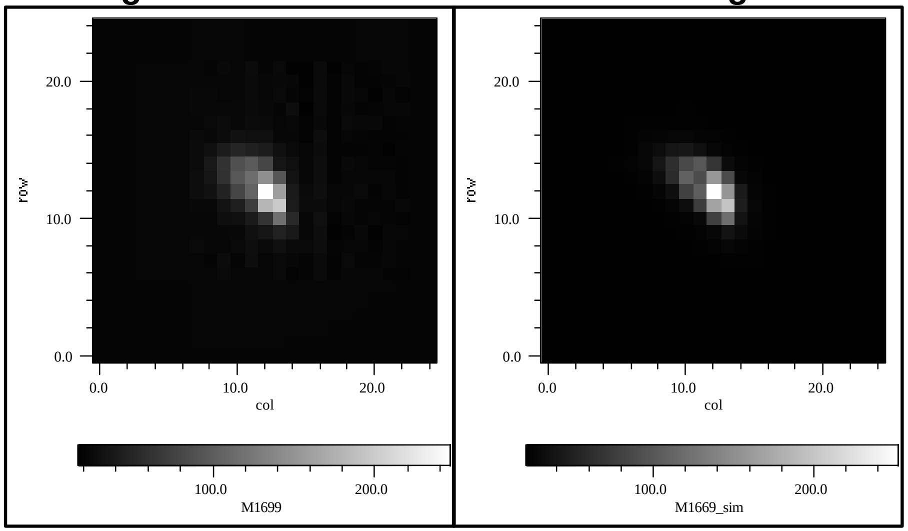
PSF Monitoring Example from WCT-2



- WCT-2 data
  - 900 nm filter
  - 0.1 sec exposure time
  - No PSF magnifier
  - Match = 0.026 RSS vs. total of 25

Mars Observer Camera Example

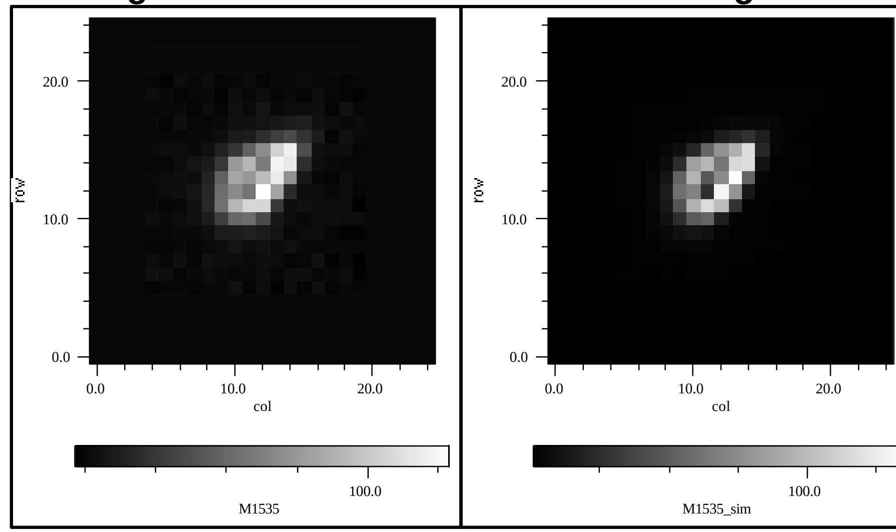
Image M1699: Actual and Simulated Images



Actual image ***Simulated image***

- Image-specific parameter results
  - **Focus: 1 Watt hub heater yields 0.1814 um**
  - **Field: 0.4485 mrad**
  - **Intensity: 2.961 (unitless)**
  - **Background: 20.828 (DN)**

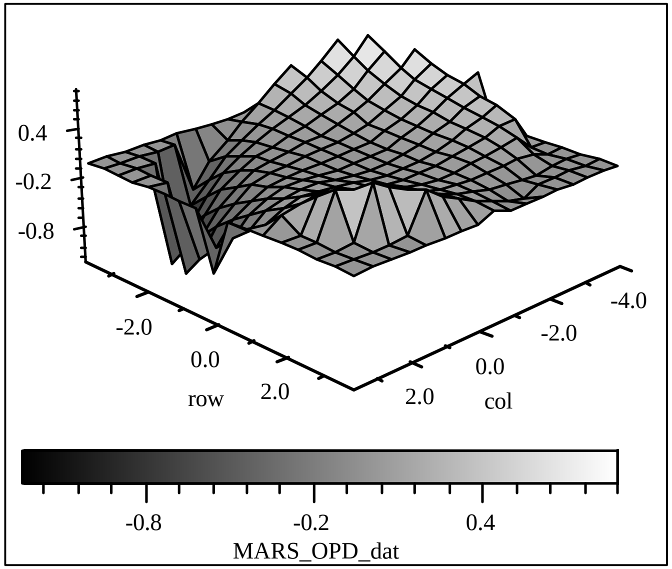
Image M1535: Actual and Simulated Images



Actual image ***Simulated image***

- Image-specific parameter results
  - **Focus: 3 Watt rim heater yields -0.2908 um**
  - **Field: 1.806 mrad**
  - **Intensity: 2.8958 (unitless)**
  - **Background: 20.498 (DN)**

- Diagnostic data taken en route to Mars
- Illustrates prescription retrieval with low resolution, low SNR, broadband data



WF Sensing and Control Is Built On...

- Good computational models
  - Embedded in WFS and WFC algorithms
  - Simulations for development before the hardware is ready
- Good analysis
- Good devices
- Good experiments
- OK optics!

Conclusion

- The JWST Government WFS&C Team has developed a complete WFS&C system that is capable of meeting mission requirements
- This system has been tested to TRL 4
- We are now working closely with TRW/Ball (the new JWST Prime Contractor), who have the ultimate responsibility for JWST
- JWST WFS&C will be at TRL 6 by the NGST Non-Advocate Review (2004?)