Jet Propulsion Laboratory
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CGI Technical Status
Phase Retrieval

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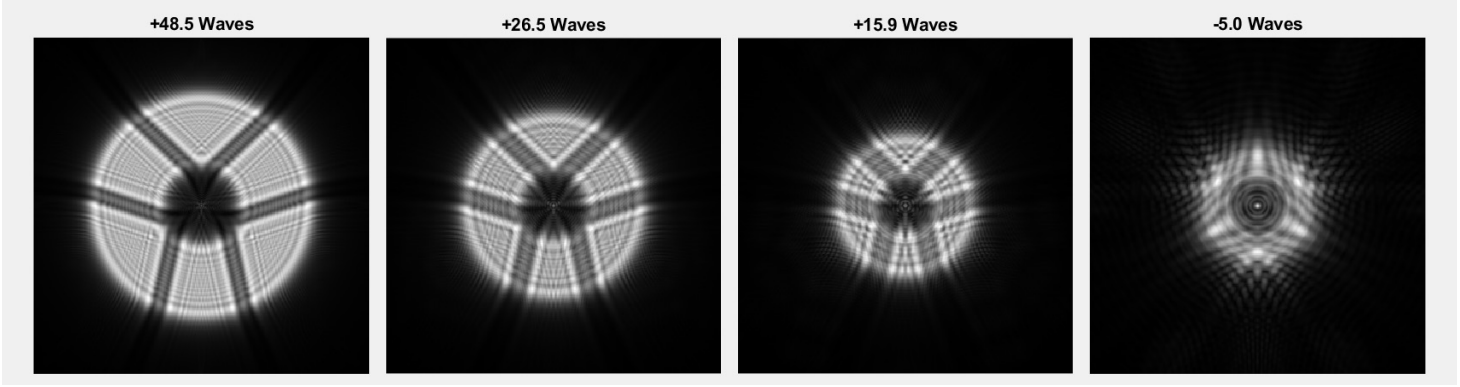
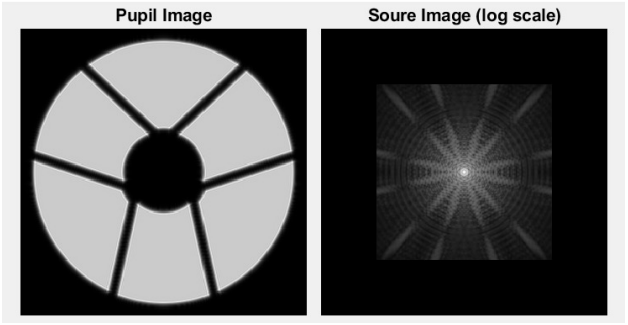
Outline

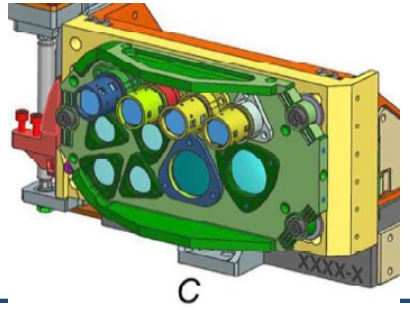
- Purposes of Phase Retrieval: Alignment and Calibration
  - DM Registration
  - Flatten Front-end Wavefront
    - Measure Total WFE and Back-end WFE
- Review of Phase Retrieval Method
  - Predicted Performance
- TVAC
  - Variation from Design and Models
  - Meets All Requirements:
    - Repeatability: Requirement < 15nm rms, TVAC Measured 8nm rms
    - Capture Range:
      - Requirement = ±108nm rms defocus, TVAC Measured ±123.1nm rms
      - Requirement = ±98nm rms ex defocus, TVAC Measured ±164.4nm rms
    - Accuracy: TVAC Measurements:
      - Small ΔZ_4 Steps Using Fine FCM Motion: 2.1nm steps with maximum nonlinearity of 0.5nm
  - Examples and Images
    - Flattening sequence
    - DM Registration
    - Back-end pinhole phase retrieval

Review of Phase Retrieval Method

Focus Diversity for Phase Retrieval: Four Defocus Lenses + Pupil Image







Review of Phase Retrieval Method

Propagation Model is in Camera-Lens Domain

a) Gerchberg-Saxton Iterations
- Defocus Diversity Near Pupil
- Recovers High Spatial Frequencies
- Propagation Model Back-and-Forth Accounts for Lenses in a Single Integration

b) Parametric Fitting

Defocus Diversity Near Star Image

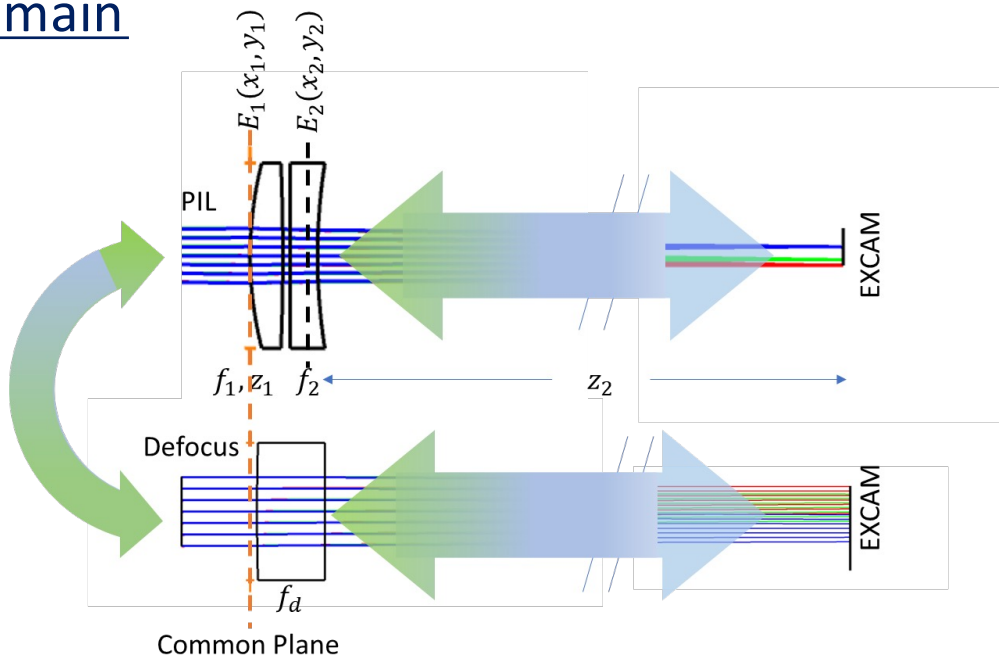
Recovers Low Spatial Frequencies

Natural Weighted Regularized Gradient Descent

Weighted by Noise Variance

c) The “Recipe”:

Alternate Between GS Iterations and Parametric Fitting



Sources of Estimation Error

- Differences Between Full Reference Model (CGISIM) and PR Propagation Model:
  - Bandwidth --- Full Model Incoherently Sums Multiple Wavelengths
  - Treatment of Doublet Lenses
  - Integration Across Camera Pixels, whereas PR Propagates Pixel to pixel
  - No Assumptions About the Common Plane
  - Fixed Parameters, Not Solved For, Potential Knowledge Errors:
    - Lens EFL (six lenses)
    - Propagation Distance Lens-to-Camera

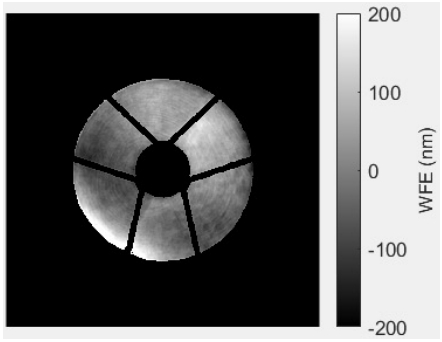
Review of Phase Retrieval Method

- Modeled Phase Retrieval
  - **"Truth" = CGISIM**

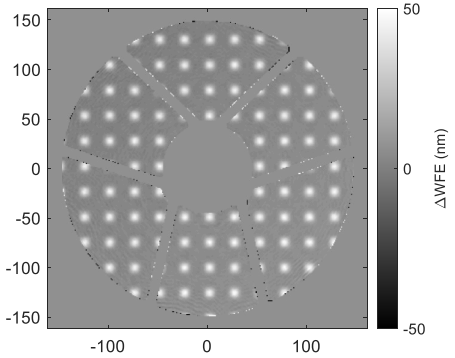
Effect	Error (nm rms)	Z4 error (nm rms)
No lens errors	2.8	-0.4
Add lens errors	4.4	0.2
Add polarization	4.4	0.2
Add 0.5% EFL knowledge error	11.5	0.3
Lens errors + 100nm defocus	4.3	-0.2
Lens errors + CCD noise	5.8	0.1

Examples:

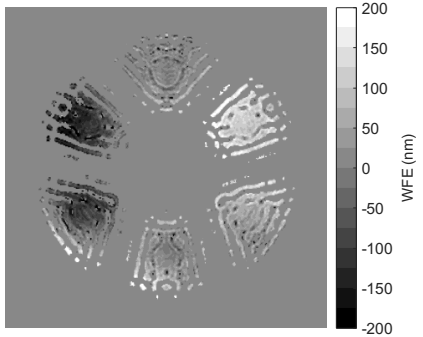
Nominal System WFE



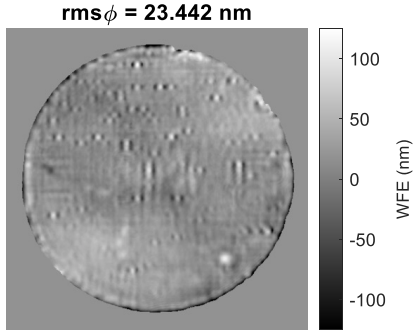
DM Registration



Shaped Pupil



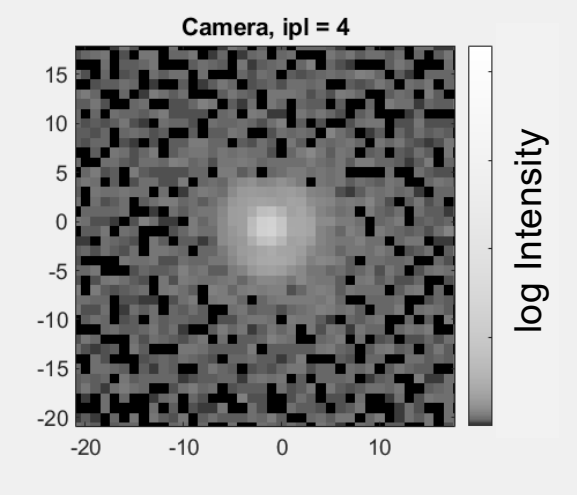
Testbed Demo



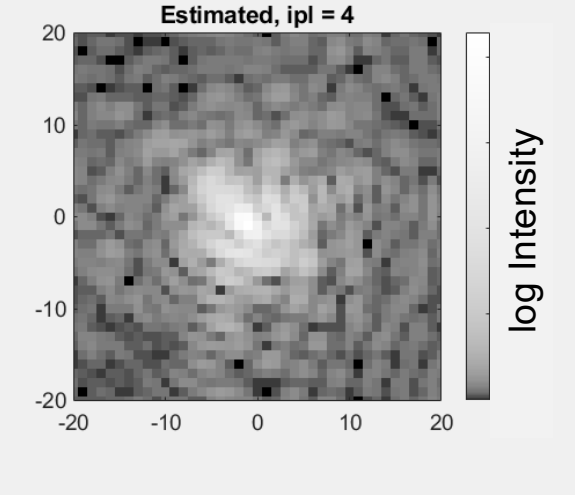
TVAC - Modifications

- Modification #1: Do Not Use DI Image
  - Phase Retrieval Attempts to Reproduce the “woven fabric” Background.
  - Impossible Because Background is Not From Propagated Light.

Measured

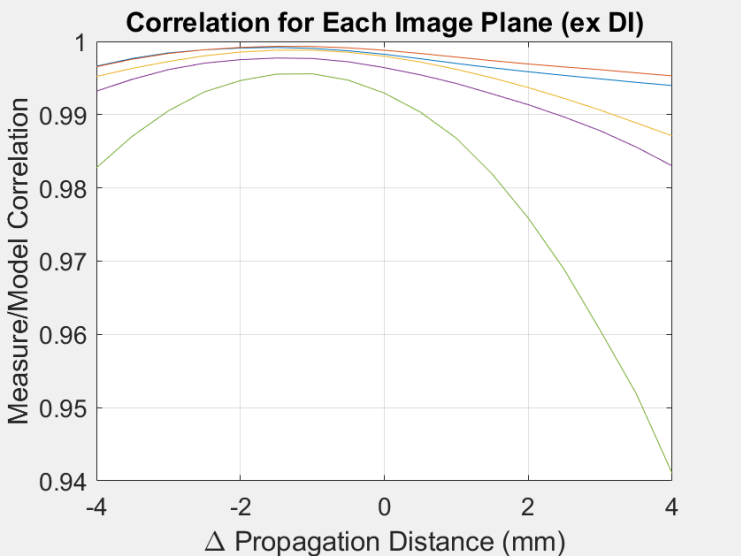


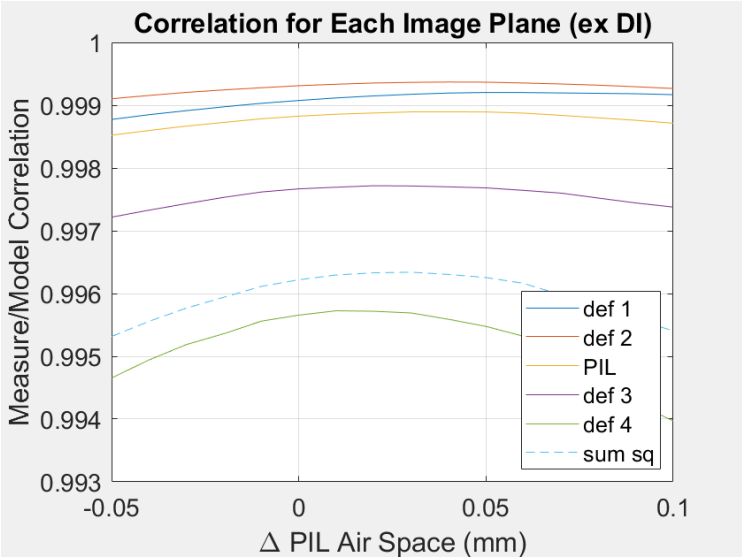
Estimated



TVAC - Modifications

- Modification #2: Propagation Model
  - Modify Propagation Distance to EXCAM by -1mm
  - Modify PIL Air-space by +0.02mm

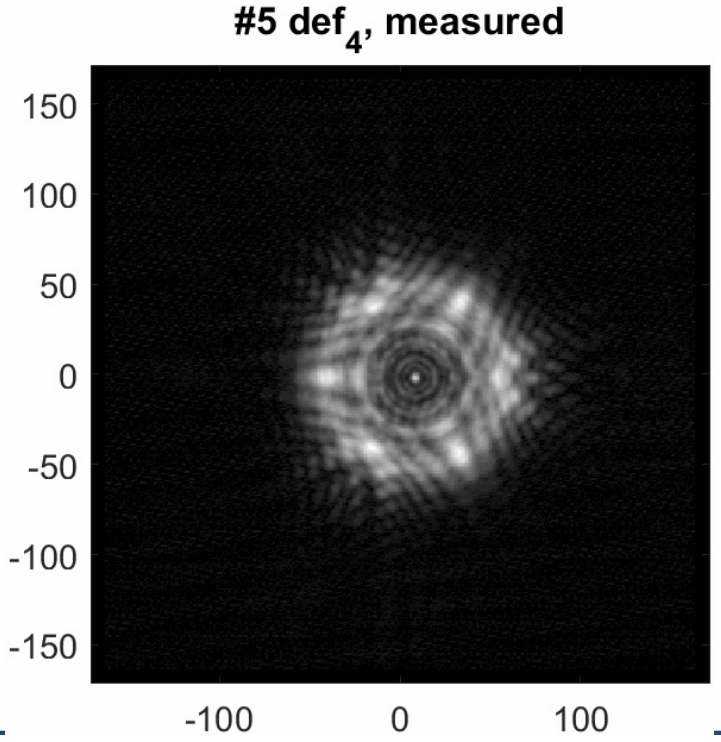




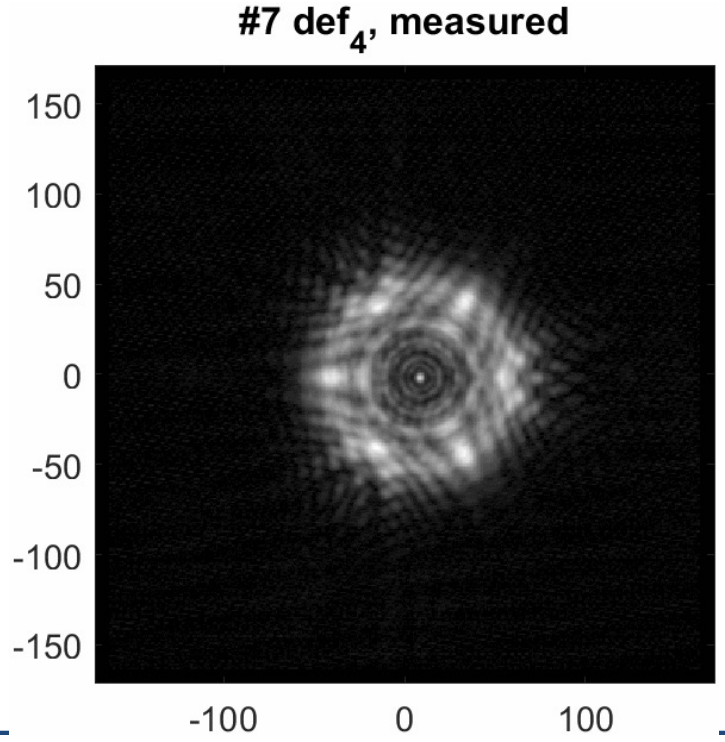
TVAC - Modifications

- Modification #3: Add Defocus 3 and Defocus 4 to GS Iterations
  - Parameters Used in Parametric Fitting Were Not Enough

Old



New



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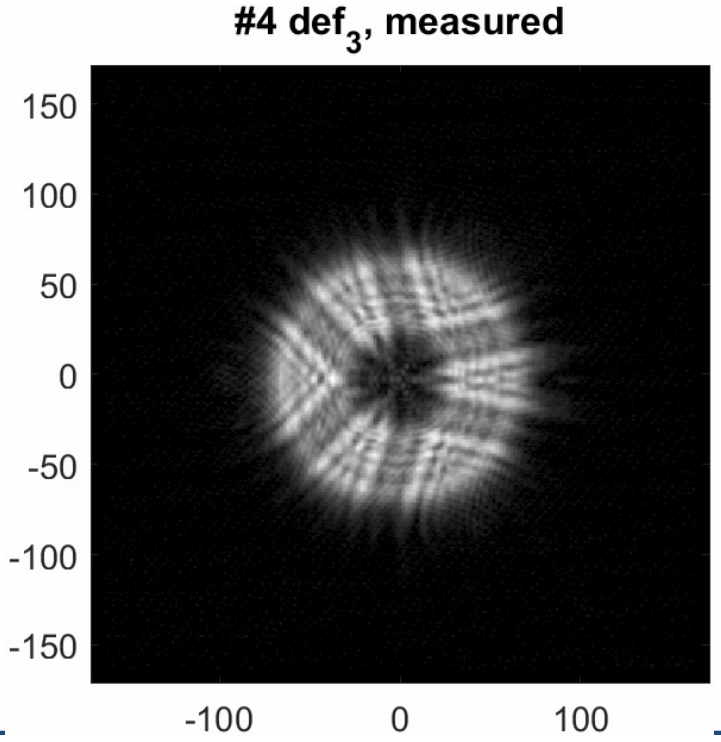
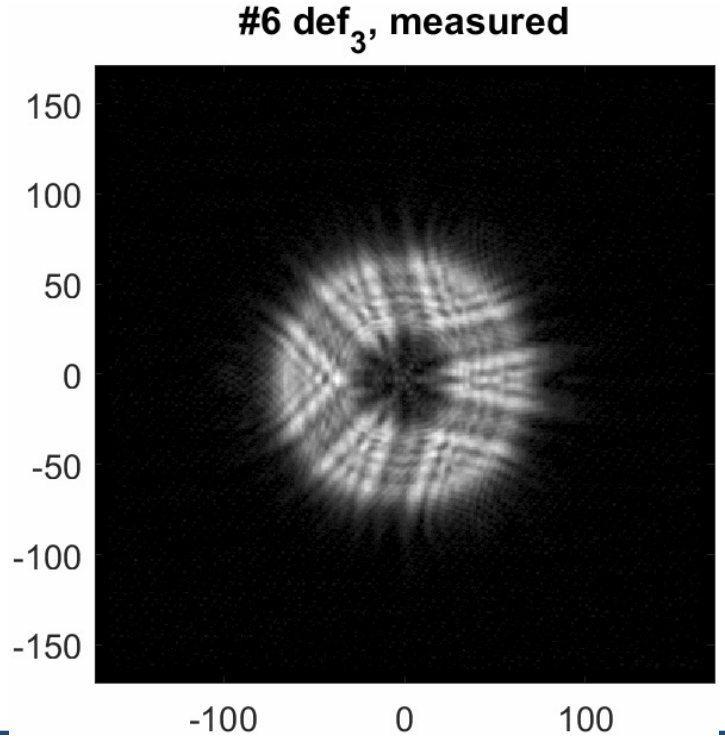


New



Summary of Phase Retrieval Requirements

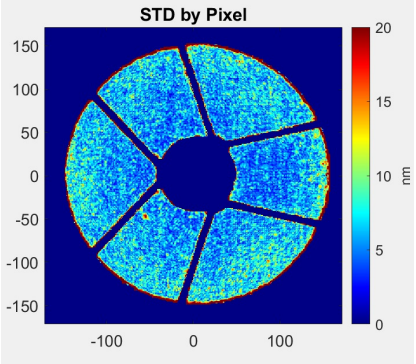
- Static Repeatability: Requirement < 15nm rms
  - TVAC: Repeated Measurement 11 Times
  - Max Raw Repeatability Error: 8.9nm rms (mostly high spatial frequency)
  - Max Zernike Fit Repeatability Error: 3.2nm

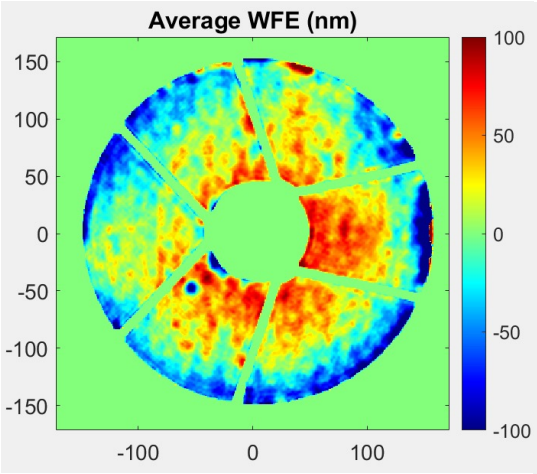
- Capture Range:
  - Requirement = ±108nm rms defocus, TVAC Measured ±123.1nm rms
  - Requirement = ±98nm rms ex defocus, TVAC Measured ±164.4nm rms

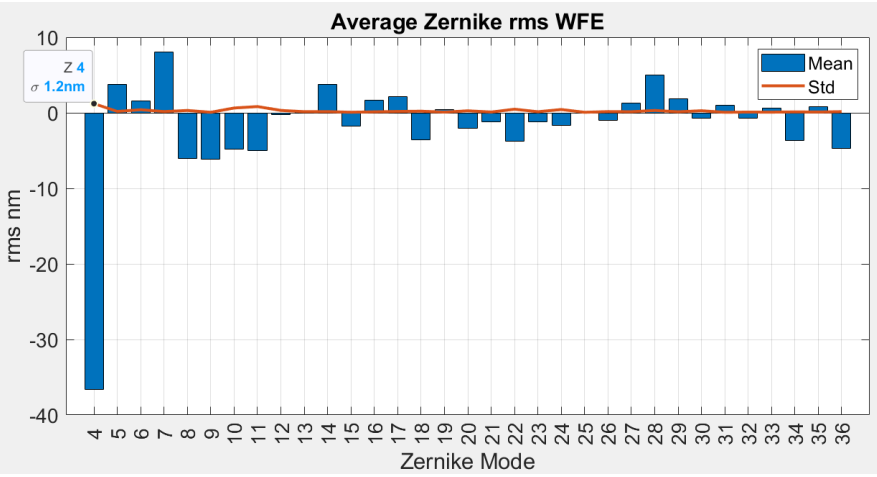
- Accuracy: Requirement < 26nm rms
  - TVAC: Measured Differential Accuracy
  - Small ΔZ_4 Steps Using Fine FCM Motion
  - Max Linearity Error of 0.5nm

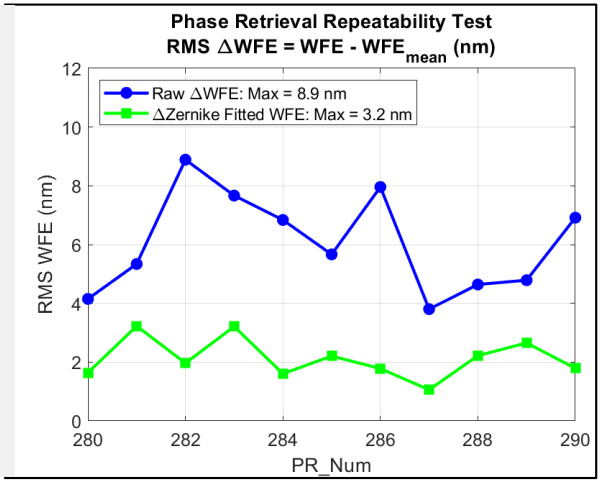
Phase Retrieval Repeatability

- 11 Sets of Phase Retrieval Images
- Before Wavefront Flattening, WFE ~ 42nm rms
- Raw (pixel by pixel) PR repeatability error:
  - $\Delta\mathbf{WFE}_{\mathrm{rms}}(PR\_NUM) = \mathbf{RMS}[\mathbf{WFE}_{\mathrm{PR\_NUM}}(\mathrm{pixel_j}) - \mathbf{WFE}_{\mathrm{mean}}(\mathrm{pixel_j})]$, max = 8.9nm
- Zernike fitted (37 terms) PR repeatability error:
  - $\Delta\boldsymbol{WFE}_{\boldsymbol{Zernike}}(PR\_NUM) = \boldsymbol{RMS}[\boldsymbol{Zernike\ Fitted}(\boldsymbol{WFE}_{\boldsymbol{PR\_NUM}}) - \boldsymbol{Zernike\ Fitted}(\boldsymbol{WFE}_{\boldsymbol{mean}})]$
  - Largest Error: Z4, $\sigma = 1.2$nm



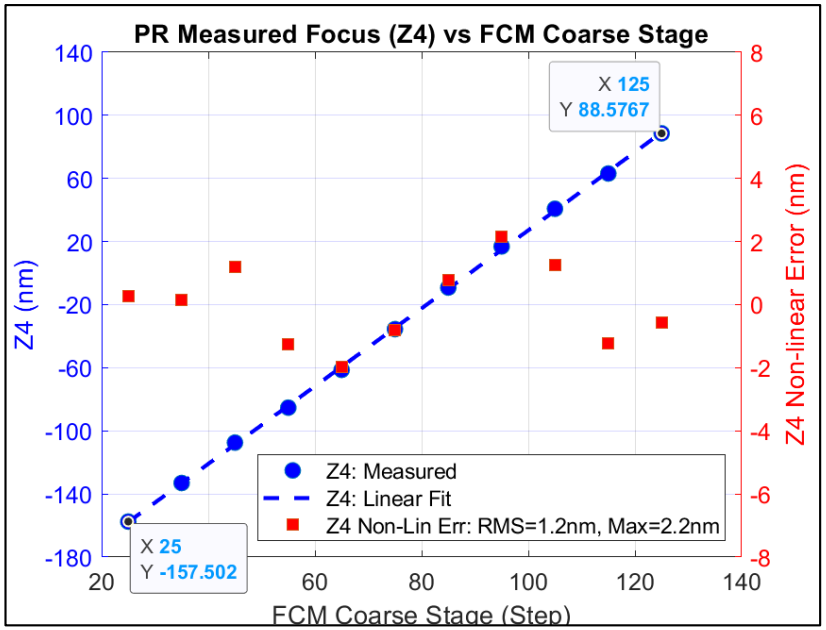






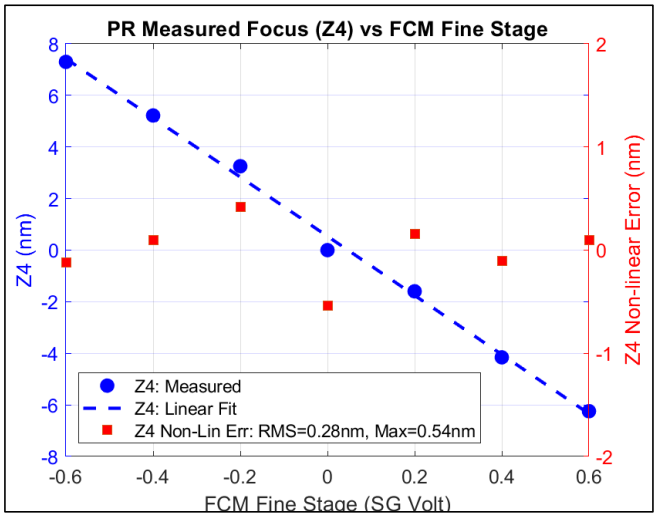
Phase Retrieval Capture Range: FCM Coarse Stage

- Measured Z4 vs FCM Coarse Stage
- Demonstrates Capture Range: -157nm to +88nm
- FCM Coarse Stage Is Not Suitable For Accuracy Comparison

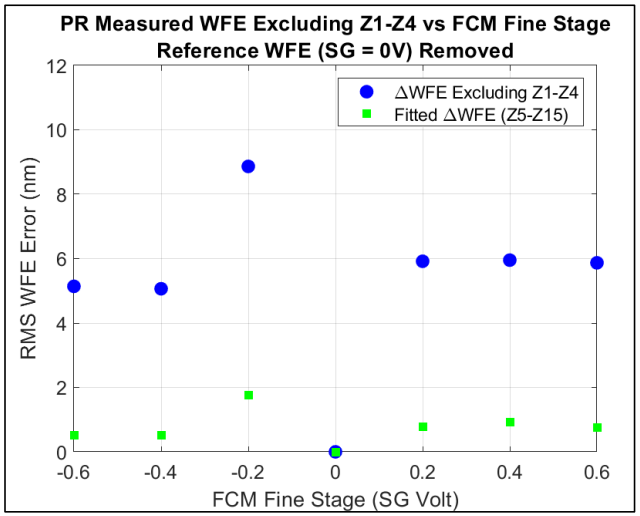


PR Accuracy: Measurement of FCM Fine Stage Scan

- FCM Fine Stage: PZT with Strain Guage Provides Delta-Focus Truth
- Recorded Phase Retrieval Images
  - Steps of 2.1nm ±0.37nm Defocus
  - Uncertainty is from Linearity + Creep
- Plot Measured ΔZ_4vs Expected ΔZ_4
  - rms Linearity Error = 0.28nm, max Linearity Error = 0.54nm

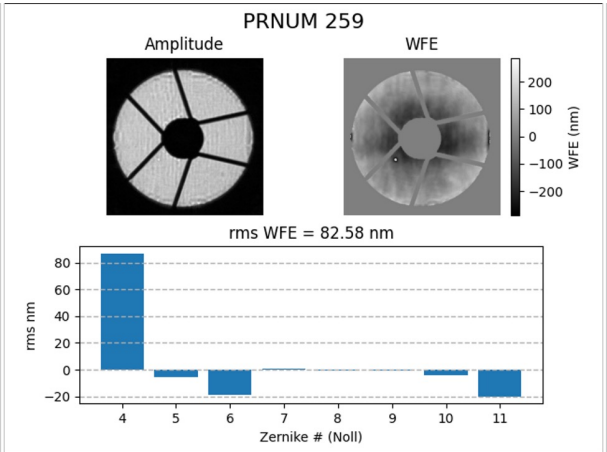


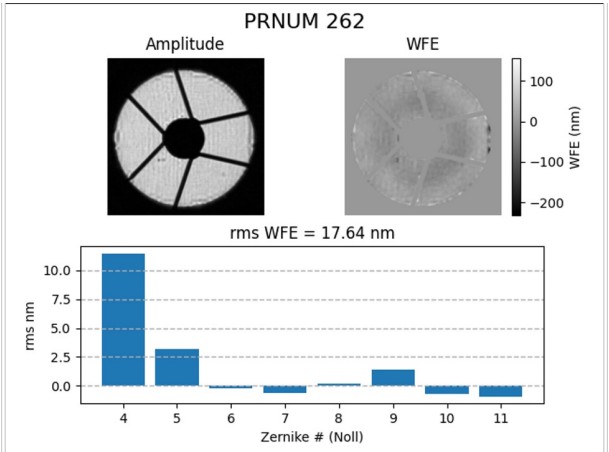
WFE ex Z4 Was Stable

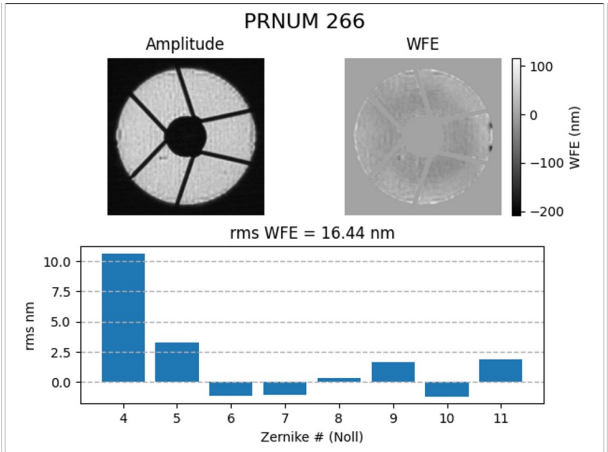


TVAC PHASE RETRIEVAL EXAMPLES

- Sequence of Wavefront Flattening



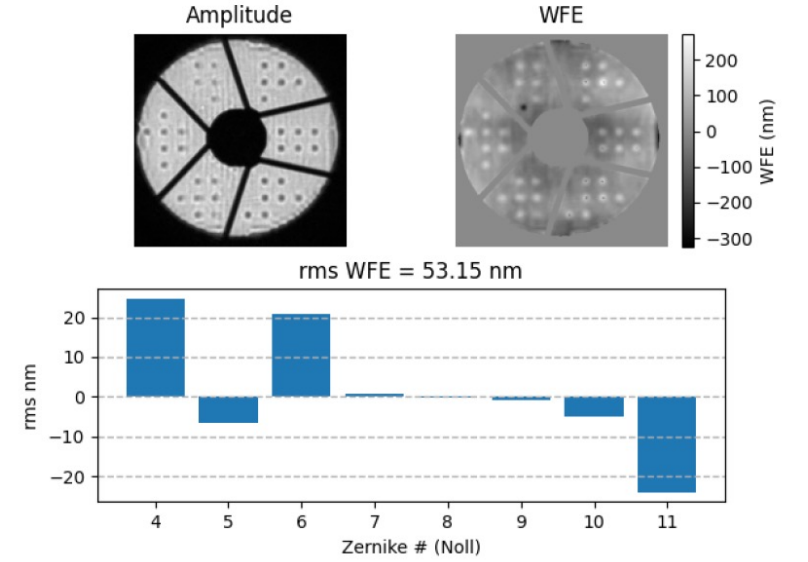




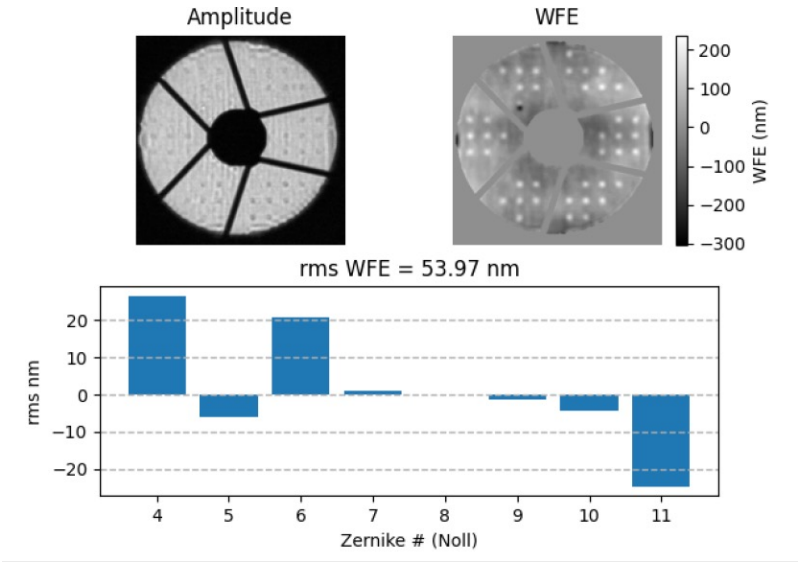
TVAC PHASE RETRIEVAL EXAMPLES

- DM Registration

DM1 Poke Grid

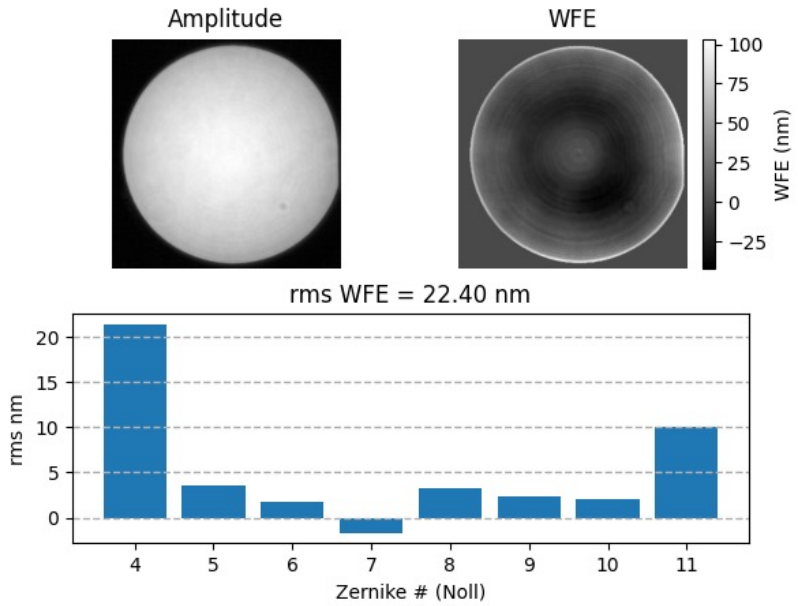


DM2 Poke Grid



TVAC PHASE RETRIEVAL EXAMPLES

- Back-end WFE
  - Pinhole at FPM



Summary

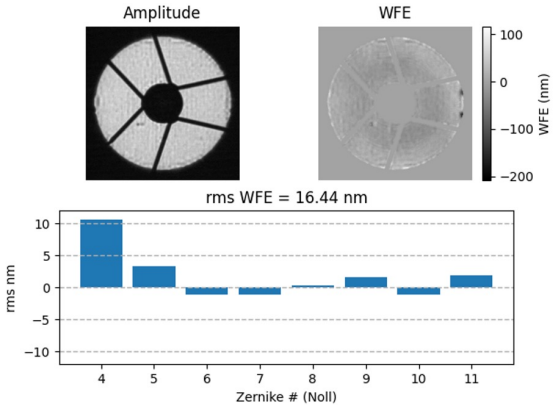
- Phase Retrieval Approach Based On Testbed Experience
- Design and Method Tested Against CGISIM
- Reality of TVAC Required Modifications
  - Most Notable – Eliminating the DI Image from the Calculation
- All Requirements Met:
  - Repeatability
  - Accuracy
  - Capture Range
- Phase Retrieval a Key Tool for Alignment and Calibration

Back-up charts

Phase Retrieval Result With Modifications

- Design vs Modified Parameters
  e.g.: “Front-end Phase Flat”
  - Change is primarily Z4:
    - Prop distance -1mm: -10nm Z4
    - PIL air-space: -5nm Z4
    - Including Def 3 & 4: 0 Z4

Before Modifications (No DI Image)



After Modifications

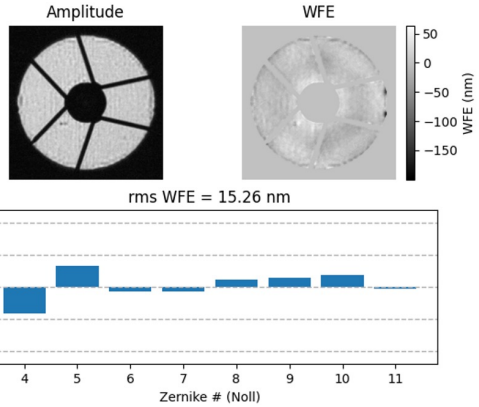


Image Correlations

	Lens	Design	Modified
GS Planes	Def 1	0.999	0.999
	Def 2	0.999	0.999
	Def 3		0.999
	Def 4		0.999
	PIL	0.999	0.998
PAR Planes	Def 3	0.995	0.999
	Def 4	0.991	0.999