Wavefront-error performance characterization for the James Webb Space Telescope (JWST) Integrated Science Instrument Module (ISIM) science instruments

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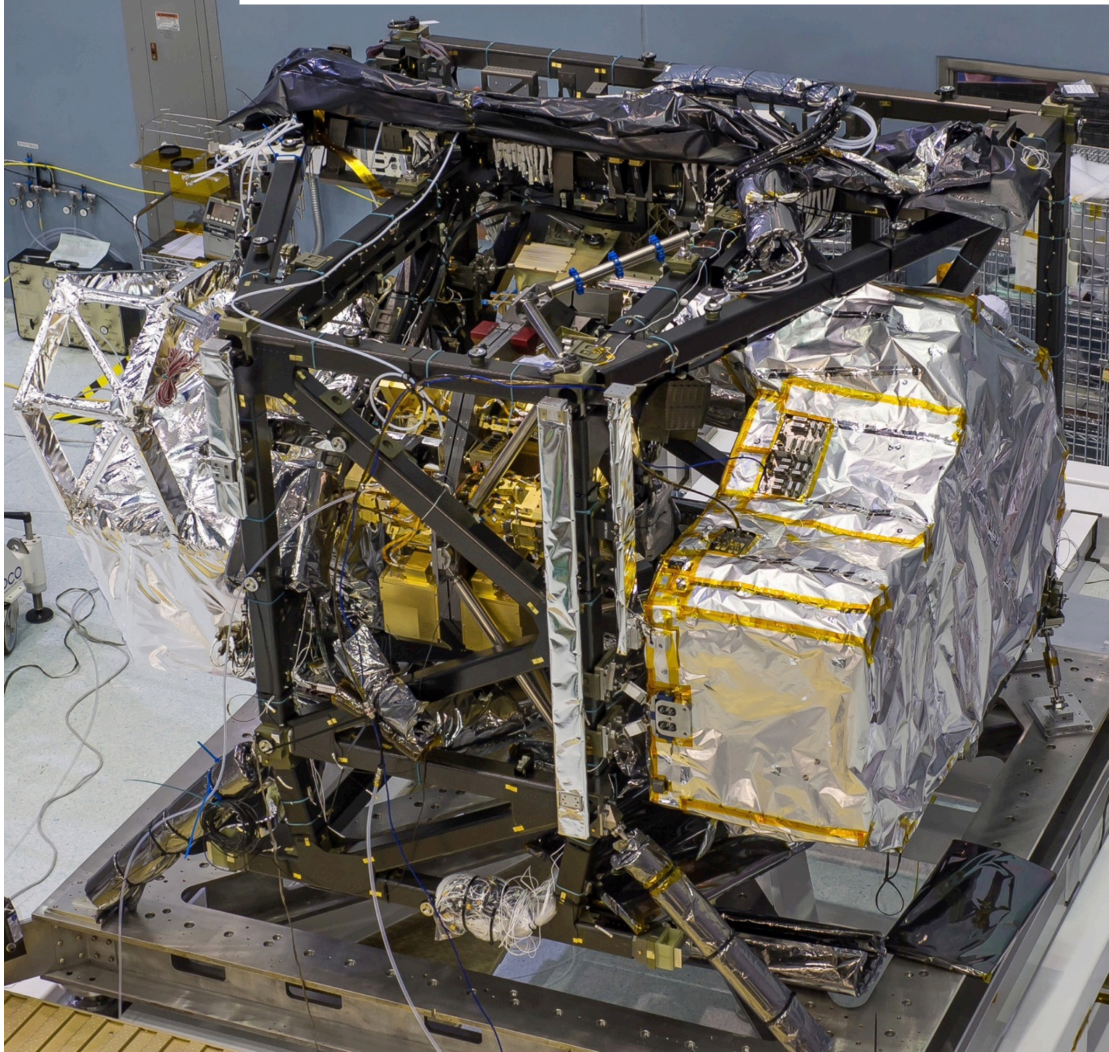


Overview

- This talk discusses characterizing the optical wavefront error of the James Webb Space Telescope (JWST) Science Instruments (SIs), comprising the Integrated Science Instrument Module (ISIM).

- This characterization was done in order to verify optical requirements on the SIs' wavefront error and focus, and to gather data needed for the JWST on-orbit commissioning sequence.

- Some of the requirements are not on the wavefront error or focus themselves, but on their uncertainties. Error budgeting is an important part of this work.

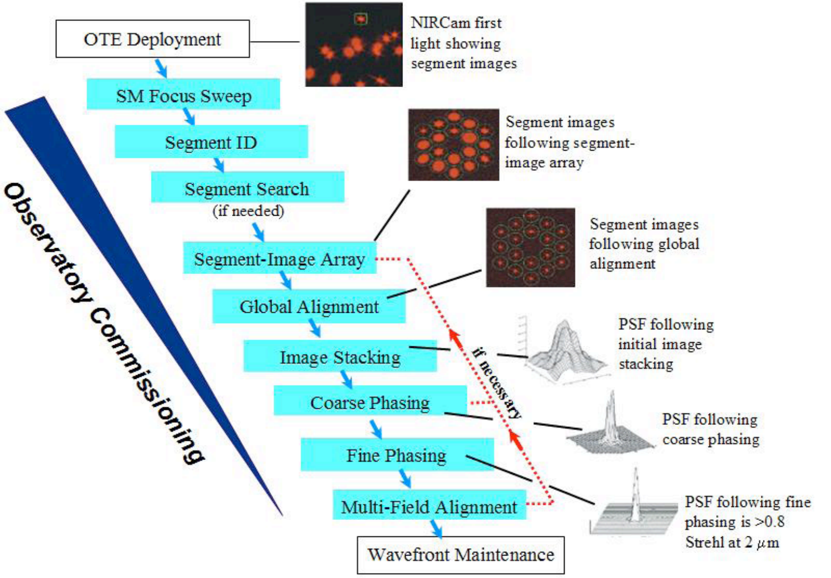
Agenda

- ISIM-level wavefront-error and focus requirements
- Method used: Image-based wavefront sensing
- Input data: Focus sweeps, OGSE calibration, and plate-scale measurements
- RMS wavefront-error characterization results
- NIRCam Coronagraphic Module trending
- Overview of wavefront-error uncertainty budget terms

ISIM-level Wavefront Error & Focus Requirements

- **RMS wavefront error** req'ts for NIRCam SW, NIRISS, and MIRI.
  - Requirements for NIRCam LW are verified at SI level
  - Guider 1 & 2 have noise-equivalent angle (NEA) req'ts instead.

- **Wavefront-error 3rd-order aberrations** on orbit are needed for **Multi-Instrument Multi-Field (MIMF)** alignment, the last step of the 9-step commissioning procedure for the JWST



ISIM-level Wavefront Error & Focus Requirements

- **Focus** knowledge for multiple field points in each SI. The ISIM-level requirements are actually for co-focus, knowing the focus of each SI field point relative to a field point in one of the NIRCam SW modules.

- **Wavefront-error stability** needs to be demonstrated to ensure that the observatory meets its performance requirements during the 14 days between maintenance/re-optimization on orbit.

ISIM-level Optical Trending

- The NIRCam instruments contain internal LEDs, mounted out-of-field in the telescope focal plane, that can illuminate the optical train of NIRCam's Coronagraphic Module (COM).

  Monitoring the stability of the images from the COM LEDs is a powerful method to monitor the long-term health and stability of NIRCam, without relying on external light sources or other OGSE.

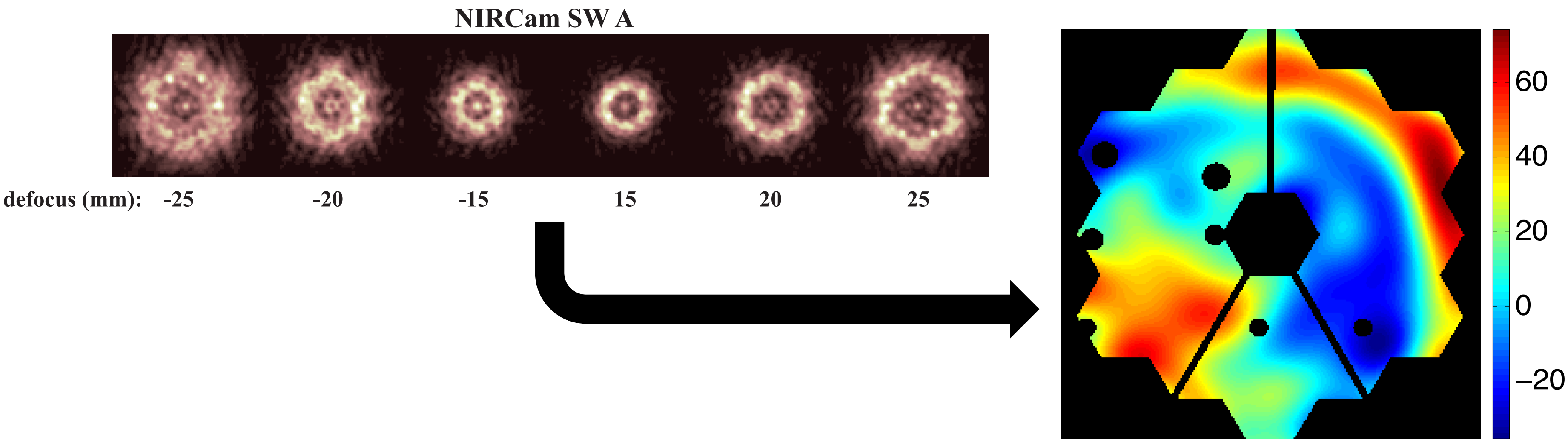
Image-Based Wavefront Sensing

- Wavefront error is measured using image-based wavefront sensing / phase retrieval.

- Wavefront sensing uses a set of images recorded using the instrument under test, and uses a computer algorithm to determine the instrument's exit-pupil wavefront error most consistent with the input images.

- The set of images is typically a *focus sweep*, a series of images with the plane of focus systematically moved between images.

Image-Based Wavefront Sensing

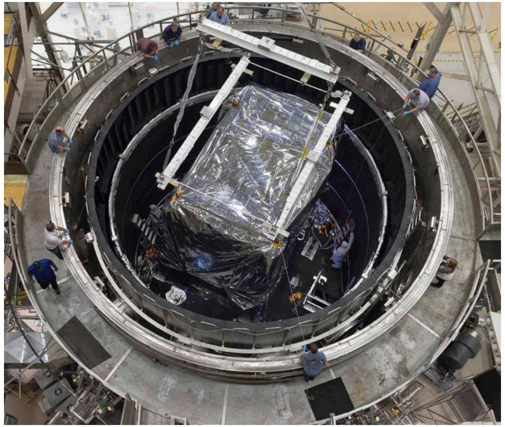


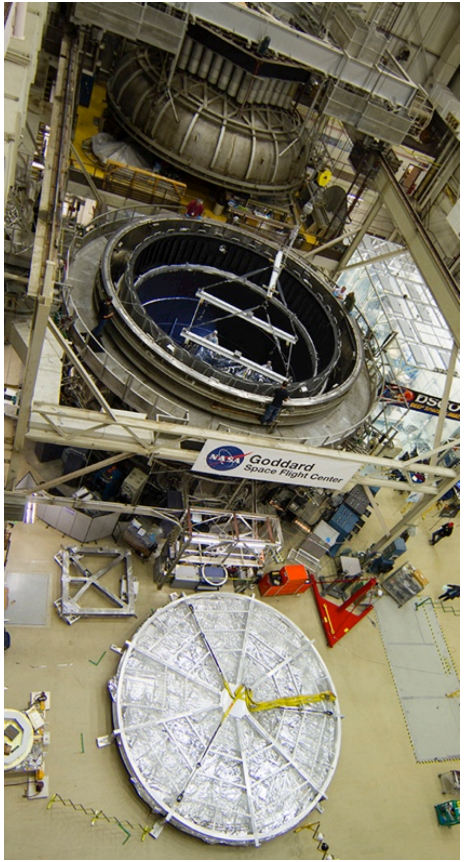
- **There are two types of wavefront-sensing algorithms:**
  - **Iterative-transform**
  - **Nonlinear optimization**

We use 4 separate algorithms on the ISIM Wavefront Sensing team, two ITA and two NLO.

ISIM Cryogenic-Vacuum Testing

- The Science Instruments (SIs) in the Integrated Science Instrument Module (ISIM) of the James Webb Space Telescope (JWST) were tested in three cryogenic-vacuum tests in the NASA GSFC's Space Environment Simulator (SES):
  - ISIM CV1RR, Aug. – Nov. 2013
  - ISIM CV2, June – Oct. 2014
  - ISIM CV3, Oct. 2015 – Feb. 2016

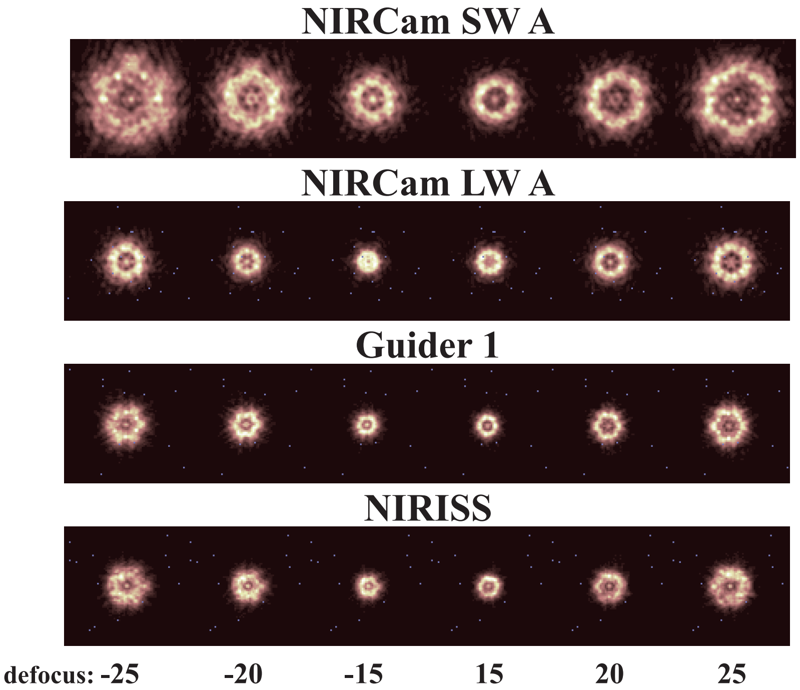


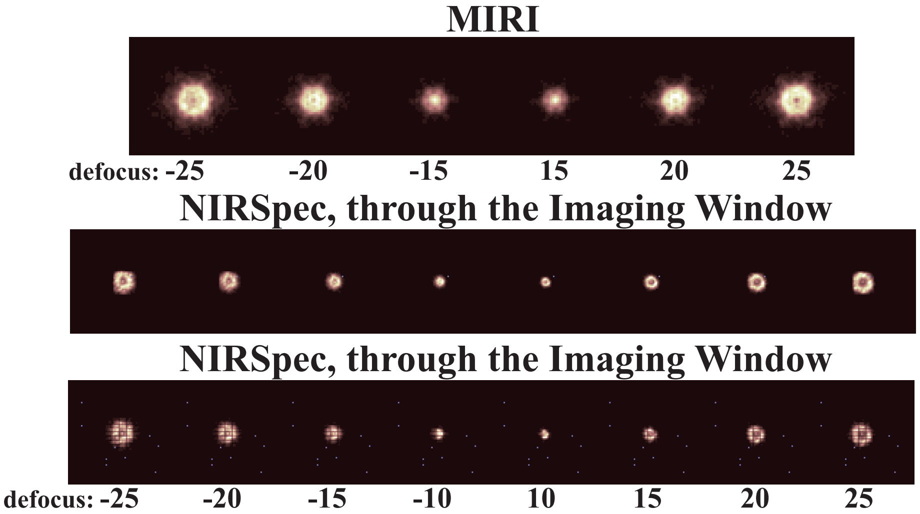


Input data: Focus sweeps

SI	Source Type	Center Light λ (μm)	SI Filter	Average Imaging f/#	Detector Pixel Size (μm)	Sampling Ratio Q
NIRCam SW	Supercontinuum	2.12	F212N	18	18	2.1
NIRCam LW	Tungsten lamp	3.23	F323N	8.8	18	1.6
FGS Guider	LED	2.1		8.1	18	0.9
FGS NIRISS	Laser diode	1.55	F157M	8.7	18	0.7
MIRI	LED w/ narrowband filter	5.6	F560W	7.1	25	1.6
NIRSpec	Laser diode	1.55	F140X	5.4	18	0.5

Input data: Focus sweeps

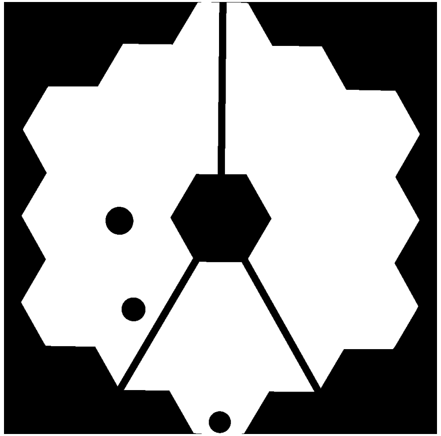




Input data: OGSE calibration

- During ISIM-level testing, the SIs were illuminated using the **OTE Simulator** (OSIM). OSIM was characterized over three cryogenic-vacuum tests at NASA GSFC.

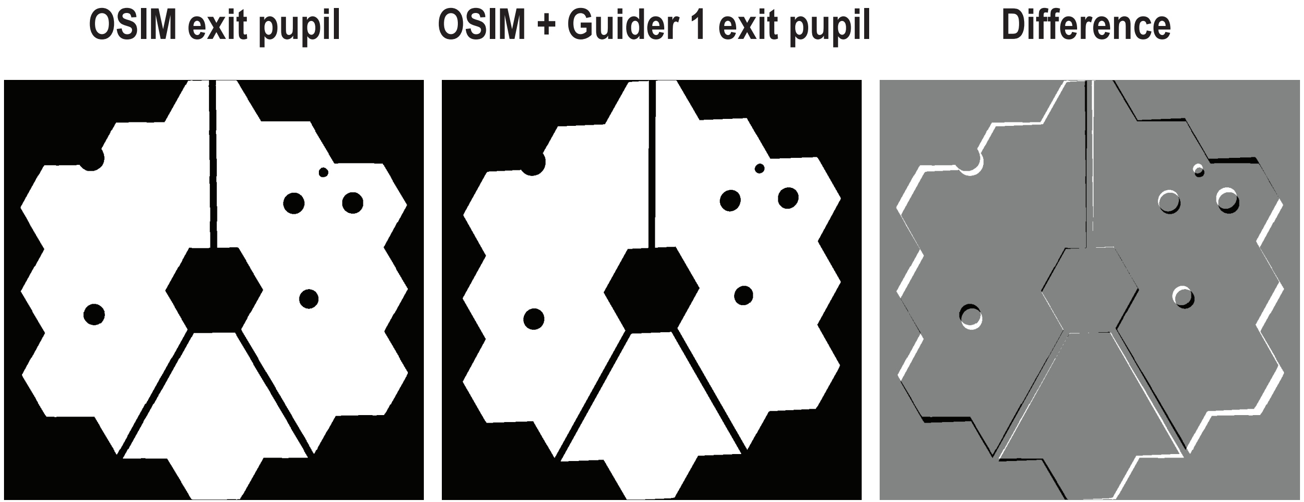
- For successful, high precision wavefront sensing, several aspects of the OSIM characterization were needed:
  - **OSIM wavefront error across its FOV**, to be removed from the results of OSIM + SI field point wavefront sensing
  - **OSIM source spectrum**
  - **OSIM source apodization**
  - **OSIM exit-pupil geometry**



Input data: Pupil distortion

- Each SI has a small amount of pupil distortion, that needs to be well characterized for exit-pupil models and for OSIM wavefront-error subtraction.

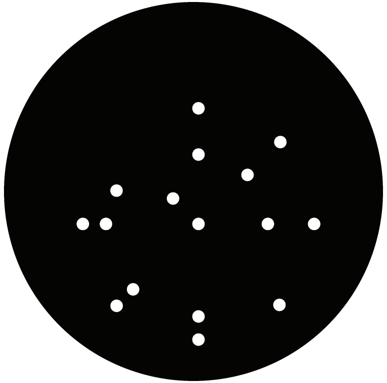
- Example from FGS Guider 1:



Input data: Pupil distortion and f/#

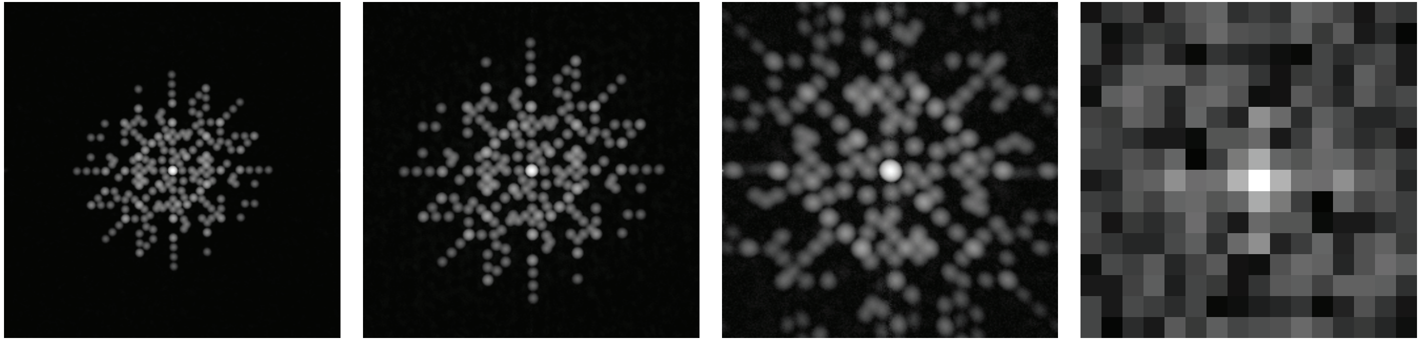
- Pupil distortion an f/# are both measured using a Pseudo-nonredundant mask (PNRM) in OSIM.

PNRM Mask



Example MTFs using the PNRM

NIRCam SW A — NIRCam LW A — Guider 1 — NIRSpec (fixed slit)

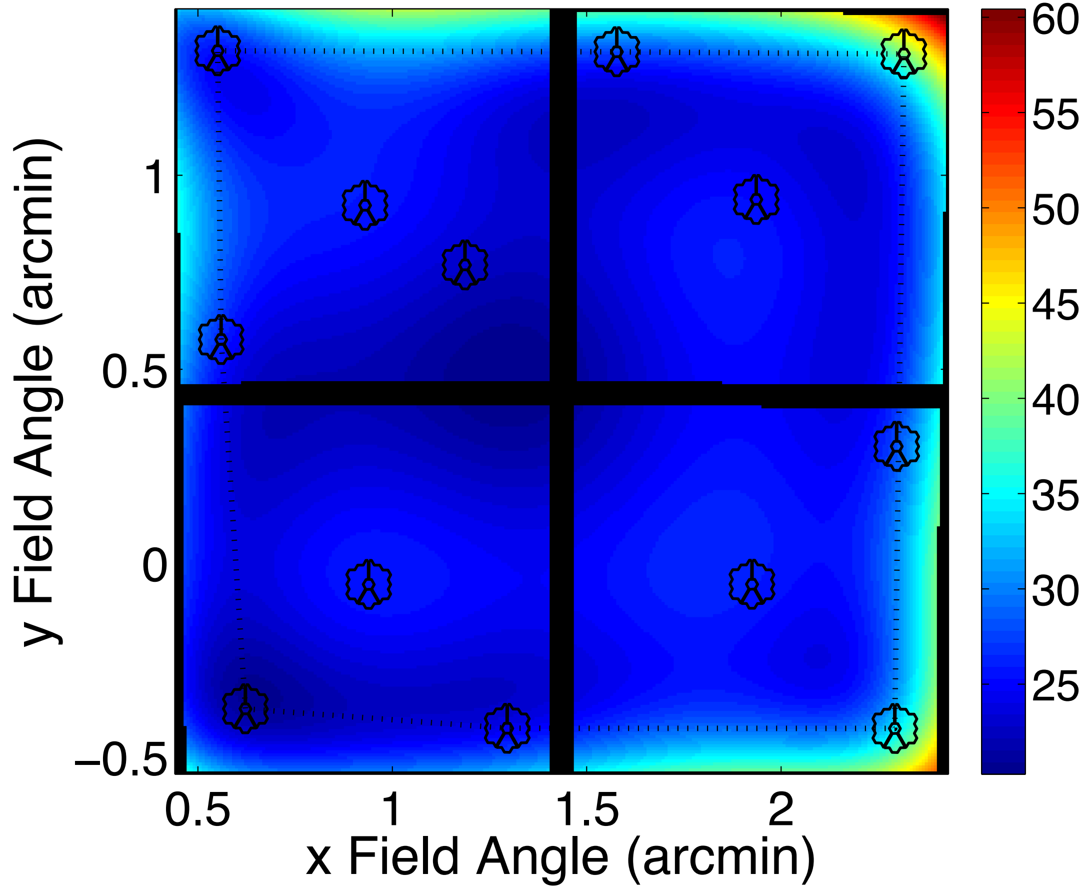


Wavefront-error performance characterization

- SI wavefront error was determined, following the steps outlined previously:
  - Focus sweeps were recorded in the SI field point, using illumination from OSIM
  - Wavefront sensing algorithms were run to determine OSIM + SI field point wavefront error maps
  - OSIM wavefront error map is subtracted, isolating the SI wavefront error

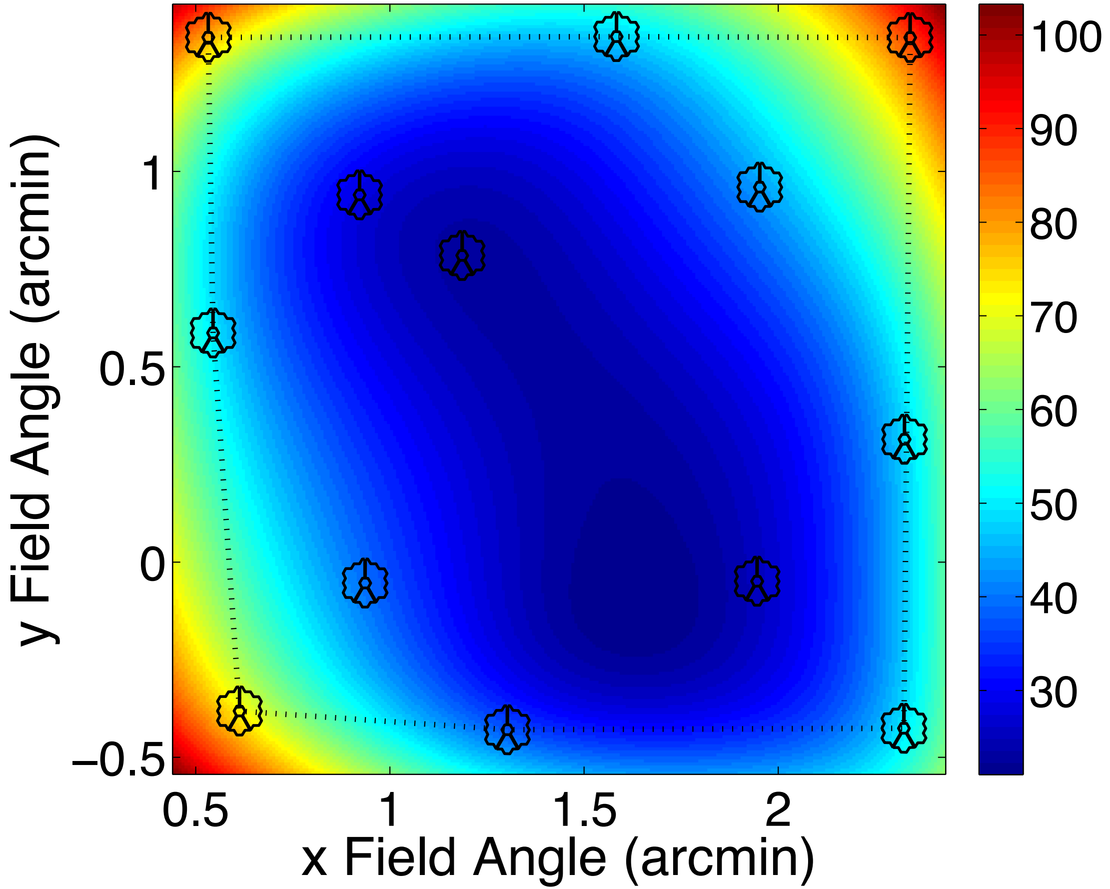
- With these maps, a variety of performance metrics can be evaluated. In the subsequent slides, we show RMS wavefront error across the field of view for each SI.
  - Data extrapolation is required to reach the edges of the FOV; the areas of extrapolation are noted by a dashed line.
  - **Extrapolation has much larger errors than interpolation!**

RMS wavefront error: NIRCam SW A



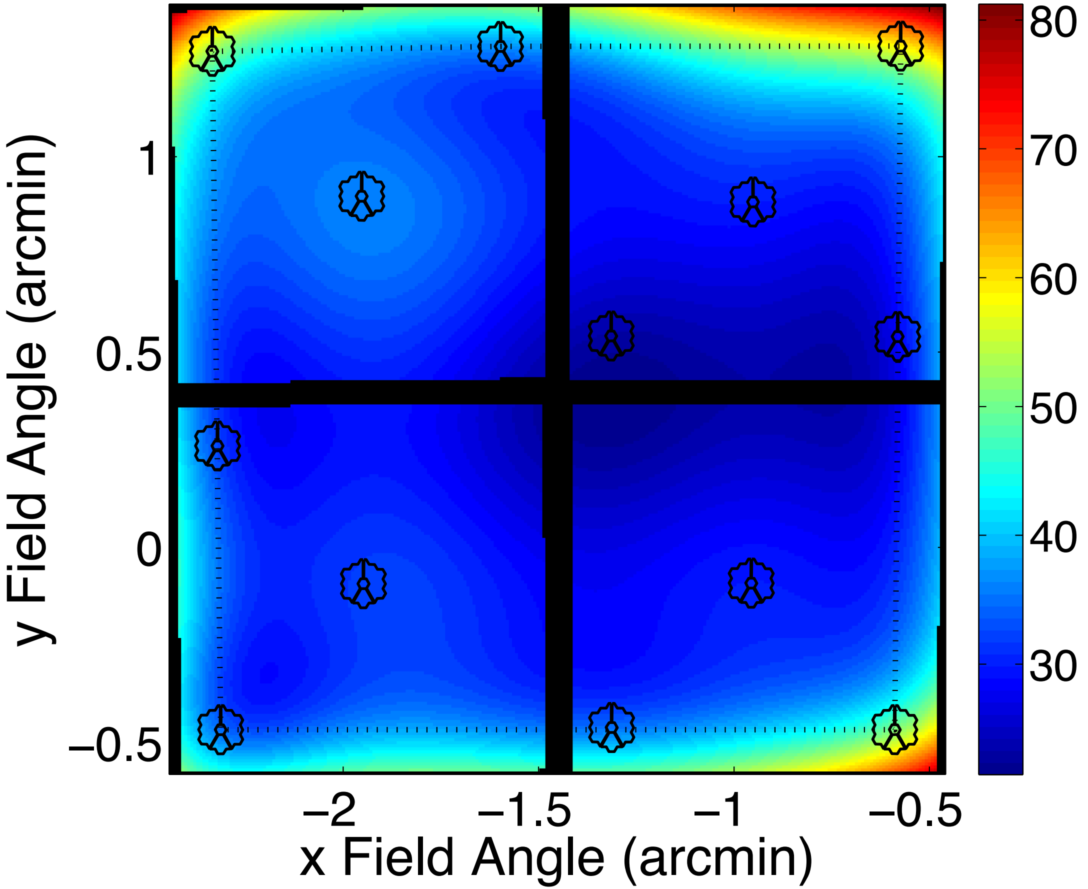
	(nm RMS)	
	Min	Max
Measured field points	21	32
Interpolated	20	39
Extrapolated	20	60

RMS wavefront error: NIRCam LW A



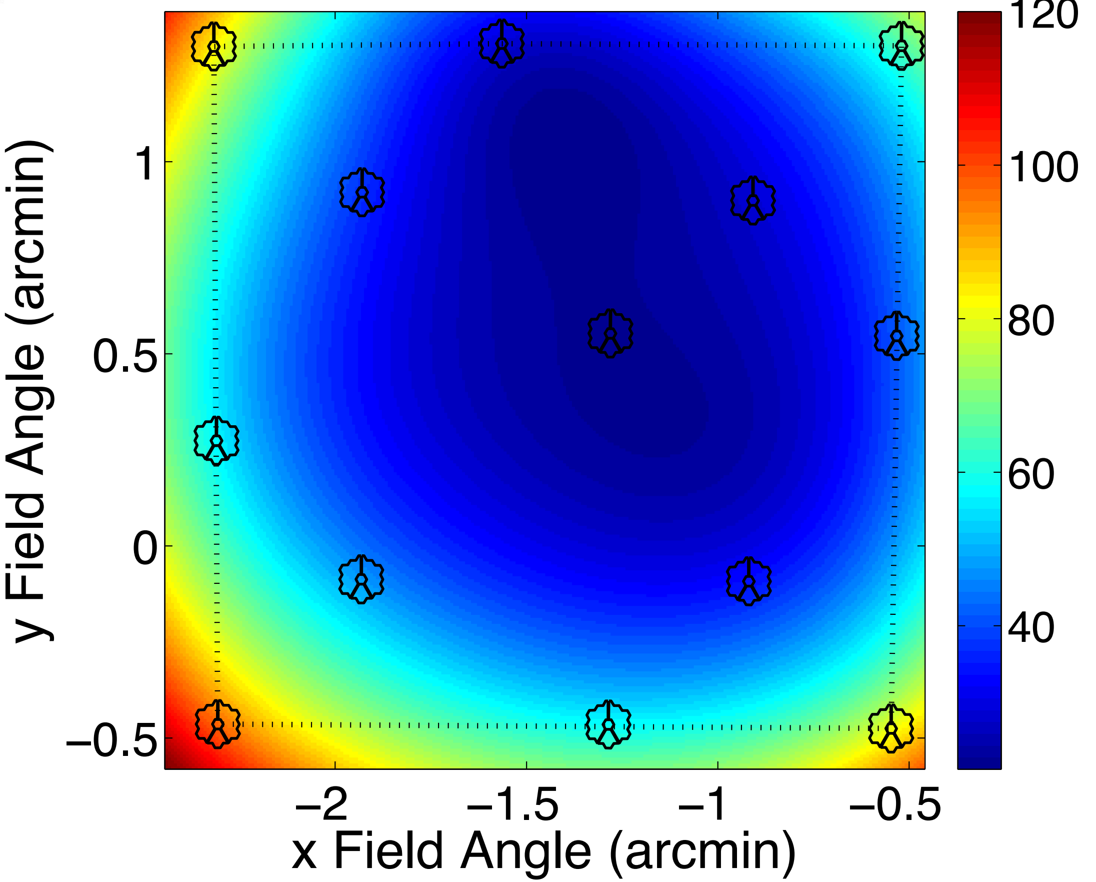
	(nm RMS)	
	Min	Max
Measured field points	24	90
Interpolated	21	90
Extrapolated	21	103

RMS wavefront error: NIRCam SW B



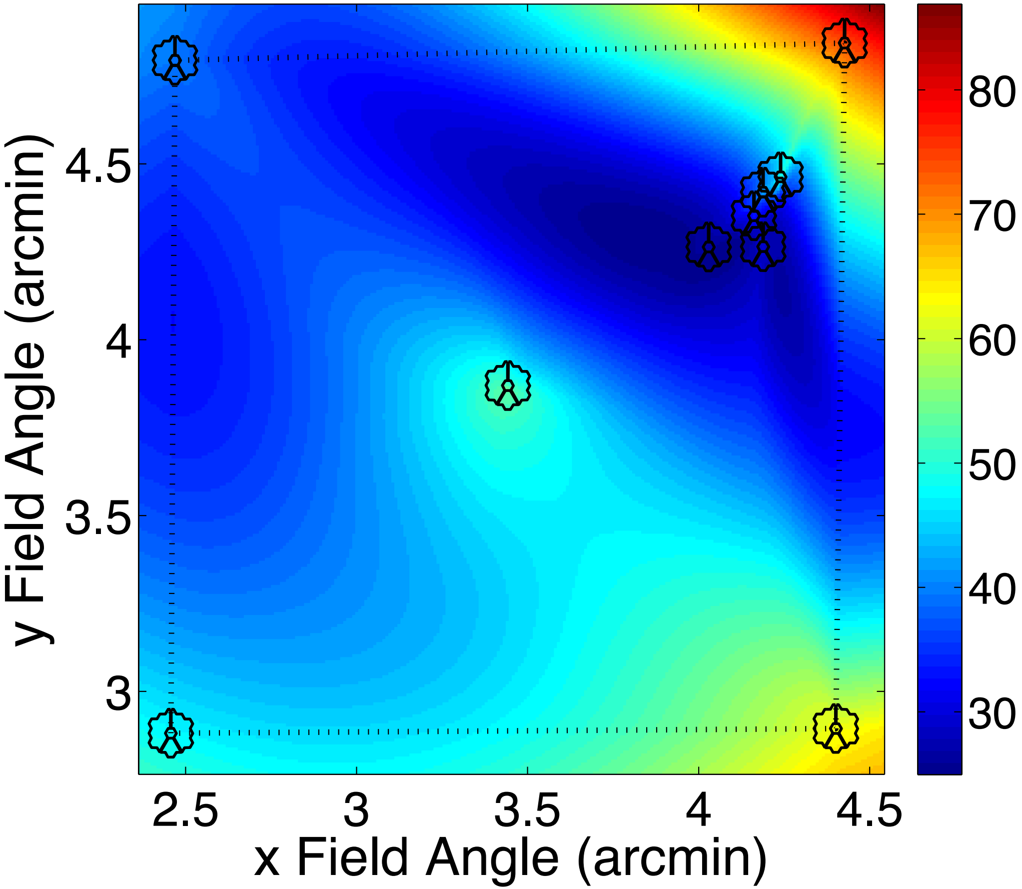
	(nm RMS)	
	Min	Max
Measured field points	26	59
Interpolated	21	59
Extrapolated	21	79

RMS wavefront error: NIRCam LW B



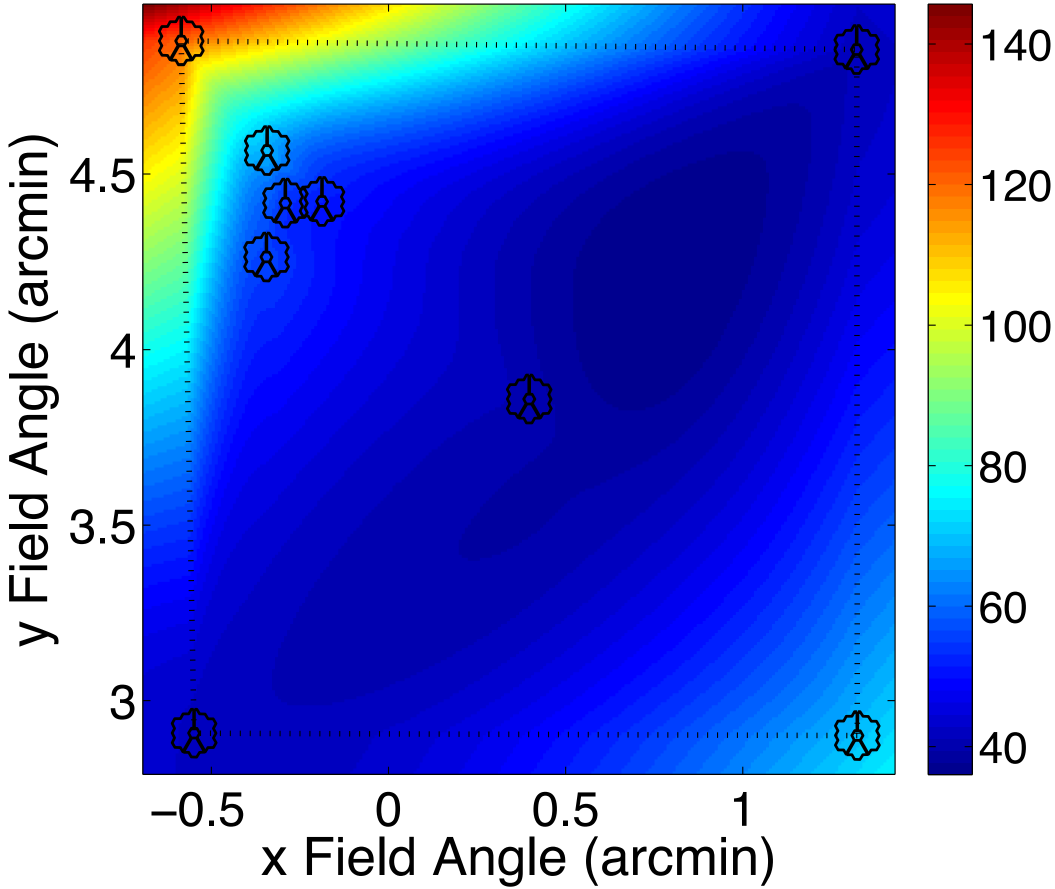
	(nm RMS)	
	Min	Max
Measured field points	24	101
Interpolated	21	101
Extrapolated	21	120

RMS wavefront error: Guider 1



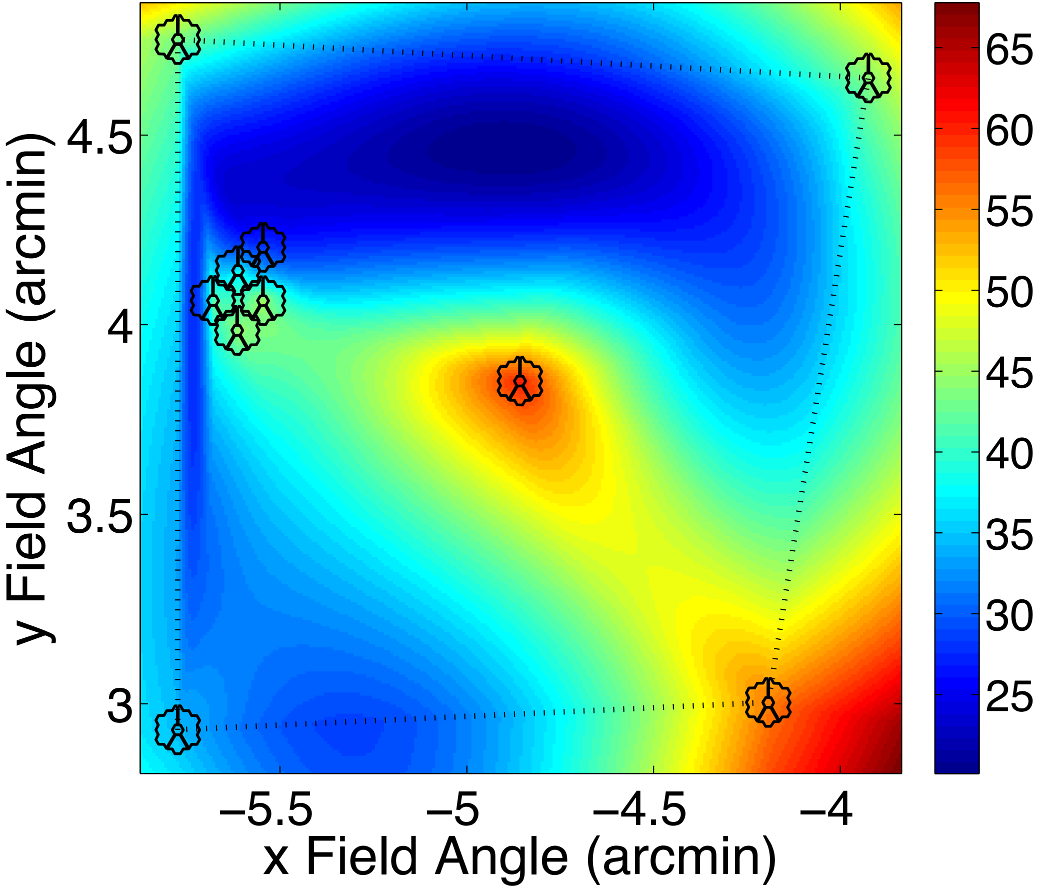
	(nm RMS)	
	Min	Max
Measured field points	29	74
Interpolated	25	74
Extrapolated	25	87

RMS wavefront error: Guider 2



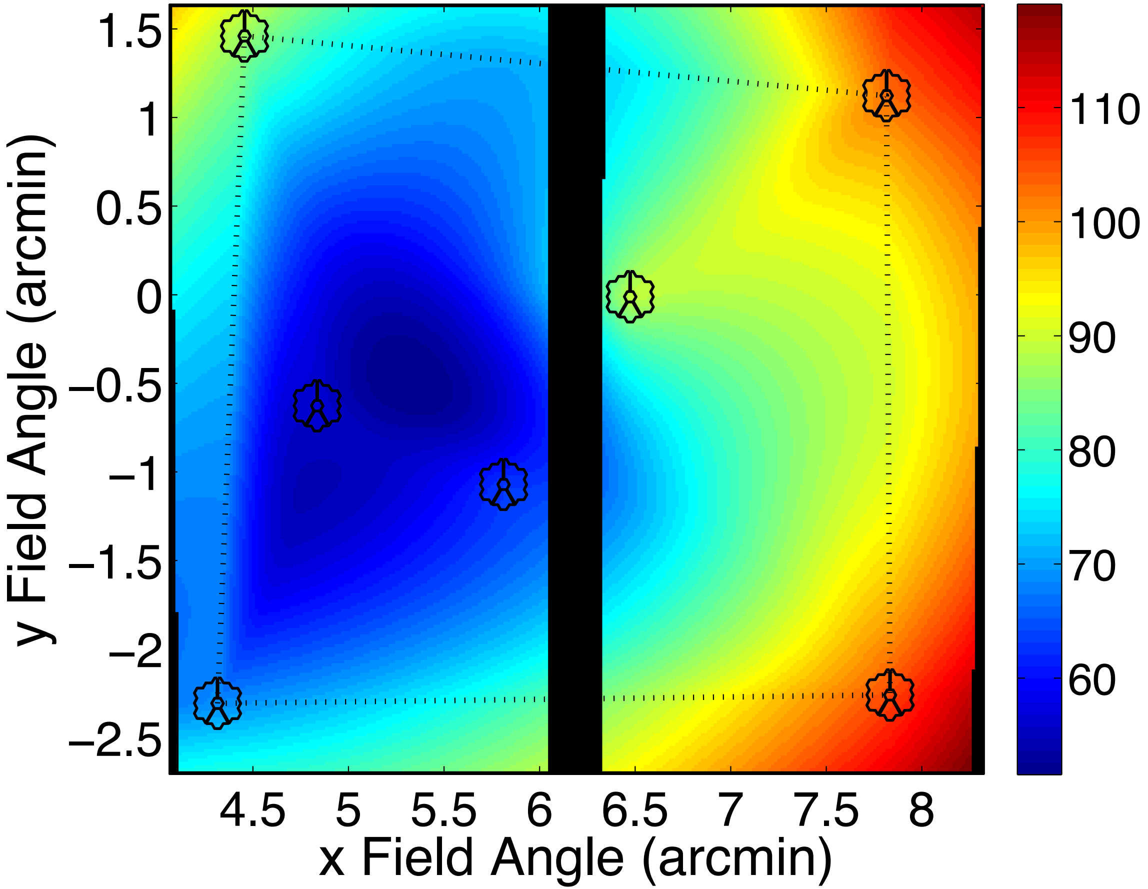
	(nm RMS)	
	Min	Max
Measured field points	40	119
Interpolated	36	119
Extrapolated	36	146

RMS wavefront error: NIRISS



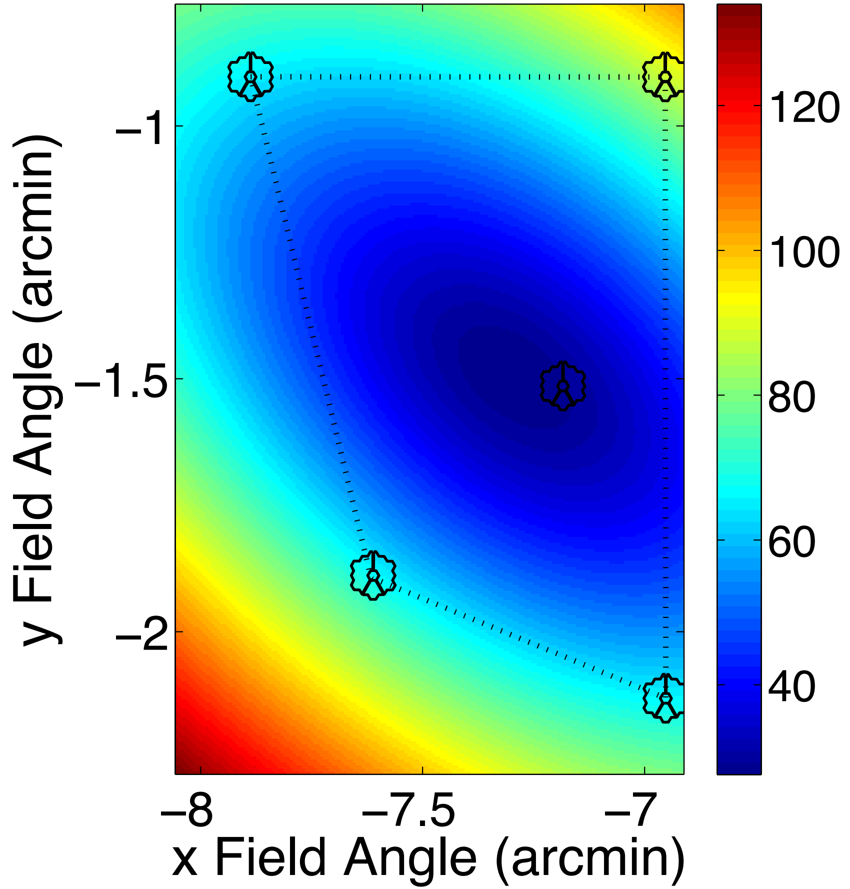
	(nm RMS)	
	Min	Max
Measured field points	29	60
Interpolated	20	60
Extrapolated	20	68

RMS wavefront error: NIRSpec



	(nm RMS)	
	Min	Max
Measured field points	58	109
Interpolated	52	109
Extrapolated	52	119

RMS wavefront error: MIRI



	(nm RMS)	
	Min	Max
Measured field points	45	86
Interpolated	28	87
Extrapolated	28	134

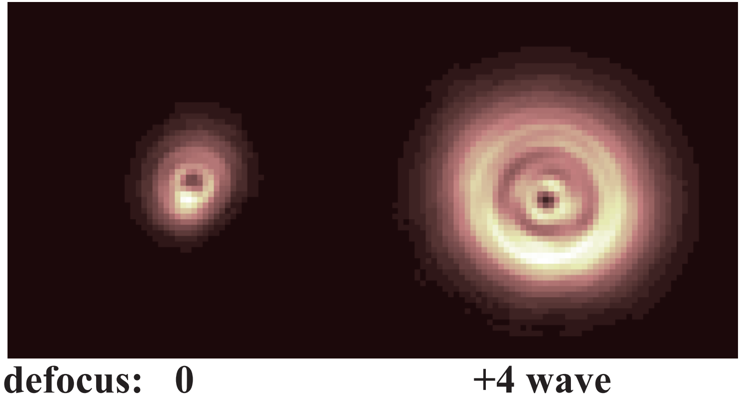
NIRCam Coronagraphic Module trending

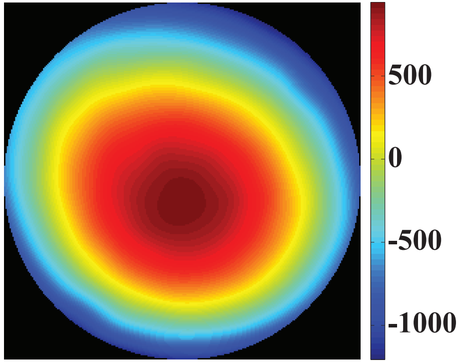
- The coronagraphic module (COM) of the NIRCam shortwave channel can be monitored with the internal LED, coupled with an "Internal Phase Retrieval" (IPR) mask, a bonded circular mask & prism in the NIRCam pupil wheel.

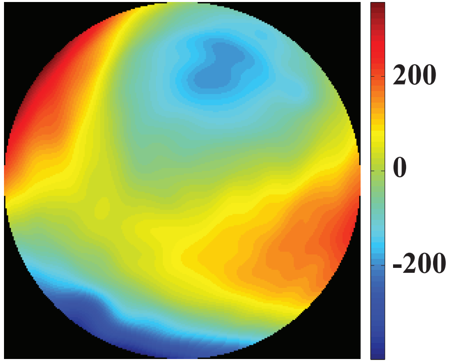
- Images can be recorded in focus* and using the +4 wave (at full pupil and 2.12um light) weak lens in the NIRCam filter wheel.

- The LED pinhole was moved so it is not conjugate with the detector, creating ~1/2 wave defocus even for the "in focus" configuration.

NIRCam Coronagraphic Module trending





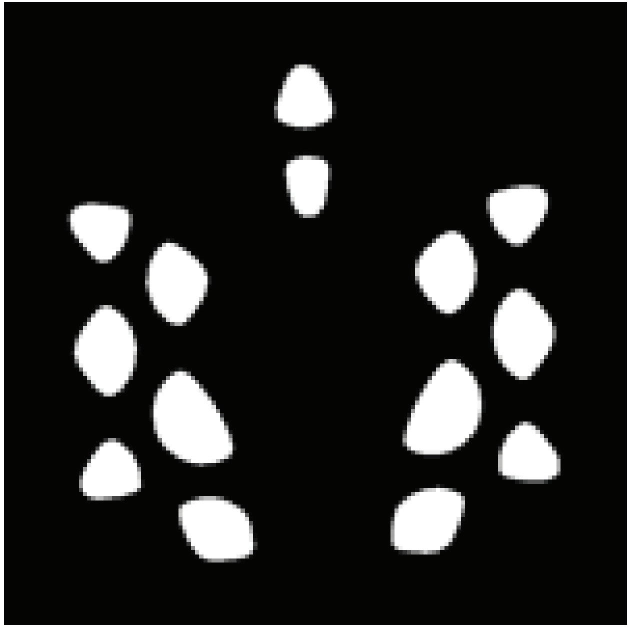


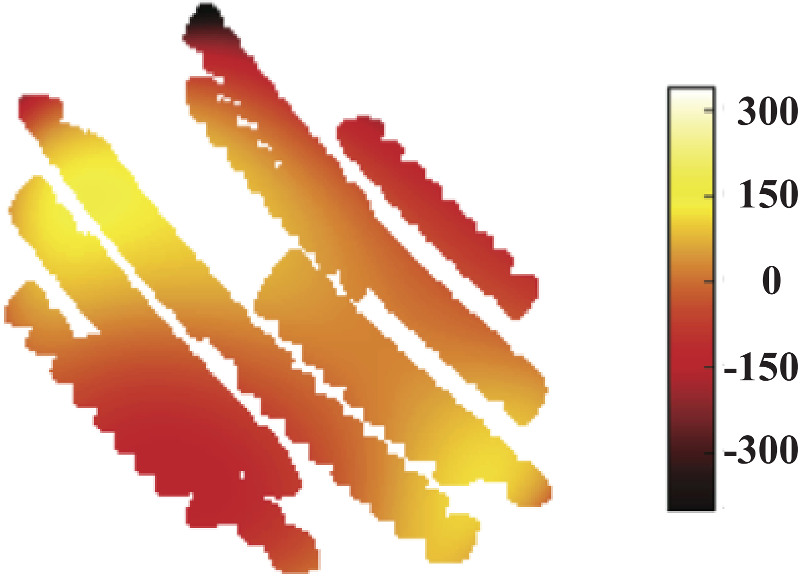
- This result was stable to < 7 nm RMS between ISIM CV2 & CV3.
- This optical path starts out of field and reaches the detector because of the IPR prism. The aberration canceling that occurs in the NIRCam field of view does not happen here. **The large RMS wavefront error in this channel is expected, not indicative of any issue when using NIRCam's regular imaging field.**

NIRCam Coronagraphic Module trending

- For the NIRCam LW COM, the IPR mask prism was installed incorrectly in the pupil wheel, and its images do not reach the detector.
- Wavefront-error trending for NIRCam LW COM was enabled using an alternate form of wavefront sensing, Transverse Translation Diversity (TTD), designed and analyzed by Moore & Fienup.
- In this TTD data, images are taken using the NIRCam LW MASKRND coronagraphic mask. This pupil covers < 20% of the full exit pupil. Instead of using a defocus sweep, a TTD sweep involves moving the mask in small angular steps across the full exit pupil.

NIRCam Coronagraphic Module trending





Wavefront-error Uncertainty Budget Terms

Key terms in our wavefront-error uncertainty budgets:

- **Uncertainties in the OSIM + SI field point wavefront-error map**
  Evaluated using Monte-Carlo simulations, creating simulated focus-sweep data consistent with detector noise properties and evaluating the data using wavefront-sensing algorithms with initial data differing from truth consistent with all known uncertainties.

Wavefront-error Uncertainty Budget Terms

- **Uncertainties in the OSIM + SI field point wavefront-error map**

Science Instrument	Iterative-Transform						Nonlinear-Optimization						Combined					
	Low		Mid		High		Low		Mid		High		Low		Mid		High	
	μ	95%	μ	95%	μ	95%	μ	95%	μ	95%	μ	95%	μ	95%	μ	95%	μ	95%
NIRCam SW	1.8	3.0	9.3	10.7	6.8	7.4	1.9	3.2	7.8	10.1	4.0	4.6	1.6	2.8	7.8	9.7	4.8	5.3
NIRCam LW	3.1	5.0	13.0	14.9	14.2	15.6	2.6	3.8	9.7	13.5	4.6	4.8	2.4	3.9	10.1	13.1	8.0	8.6
MIRI	12.1	19.3	40.6	48.1	6.6	7.9	6.9	10.2	19.3	24.9	4.2	6.5	7.1	10.1	23.8	27.2	5.1	6.8
FGS Guider 1	4.4	6.2	9.6	11.8	7.0	7.4	3.2	5.1	6.0	7.8	1.2	1.5	3.4	4.8	6.4	7.7	3.6	3.9
FGS Guider 2	5.8	7.3	14.5	16.4	17	17.7	3.0	4.9	6.6	8.7	1.6	1.8	3.6	4.9	8.6	10.2	8.6	9.0
FGS NIRISS	3.8	5.3	9.6	11.2	6.7	7.0	2.1	3.8	4.7	6.4	1.1	1.3	2.3	3.4	5.9	7.0	3.5	3.7
NIRSpec	28.7	39.3	10.7	13.8	n/a	n/a	TB	TB	TB	TB	TB	TBR	28.7	39.3	10.7	13.8	n/a	n/a

Wavefront-error Uncertainty Budget Terms

- **Uncertainties in the OSIM field point wavefront-error map**
  Evaluated by the OSIM team as part of the delivery of OSIM.
  Top-level wavefront-error requirements are:
  - **≤ 20 nm RMS uncertainty for the full OSIM wavefront-error map**
  - **≤ 10 nm RMS uncertainty for any 3rd order Zernike aberration**

Wavefront-error Uncertainty Budget Terms

- **Uncertainties due to launch vibration & acoustics**
  Evaluated using wavefront-error map changes between ISIM CV2 & CV3.ISIM underwent vibration & acoustics testing between the cryo-vac tests, but SIs also had detector SCAs and other equipment replaced.

- **Uncertainties in the 1g to 0g transition and SES test chamber to on-orbit thermal profile**
  Evaluated using STOP modeling. Please see:
  R. Gracey et al., "Structural, thermal, and optical performance (STOP) modeling and results for the James Webb Space Telescope integrated science instrument module," in Modeling III, talk 9911-48, 28 June at 16:50