National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

MEMS AO for planet finding

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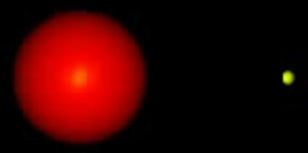
Objectives

- **Extrasolar planets are hard to see**
  - Star bright
  - Planet dim
- **200-300 identified (so far)**
- **ε Eridani has a planet. Probably.**
  - 1.5 x Jupiter mass
  - 3.4 AU
  - 7 year orbit

Distances compressed 100x

Objectives

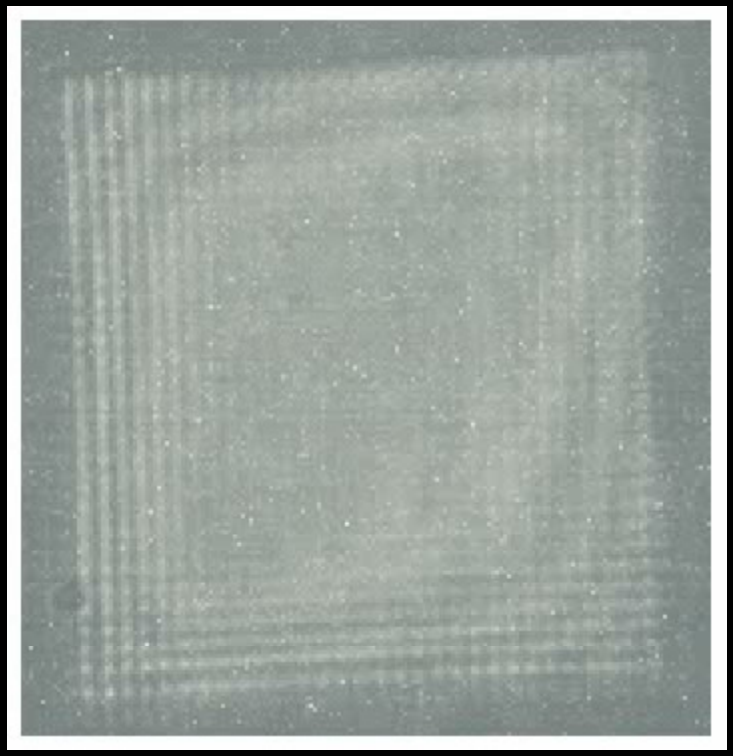
- **Extrasolar planets are hard to see**
  - Star bright
  - Planet dim
- **200-300 identified (so far)**
- **ε Eridani has a planet**
  - 1.5 x Jupiter mass
  - 3.4 AU
  - 7 year orbit
- **Visible from Earth**
  - Almost
  - Need a clever trick



Clever Trick

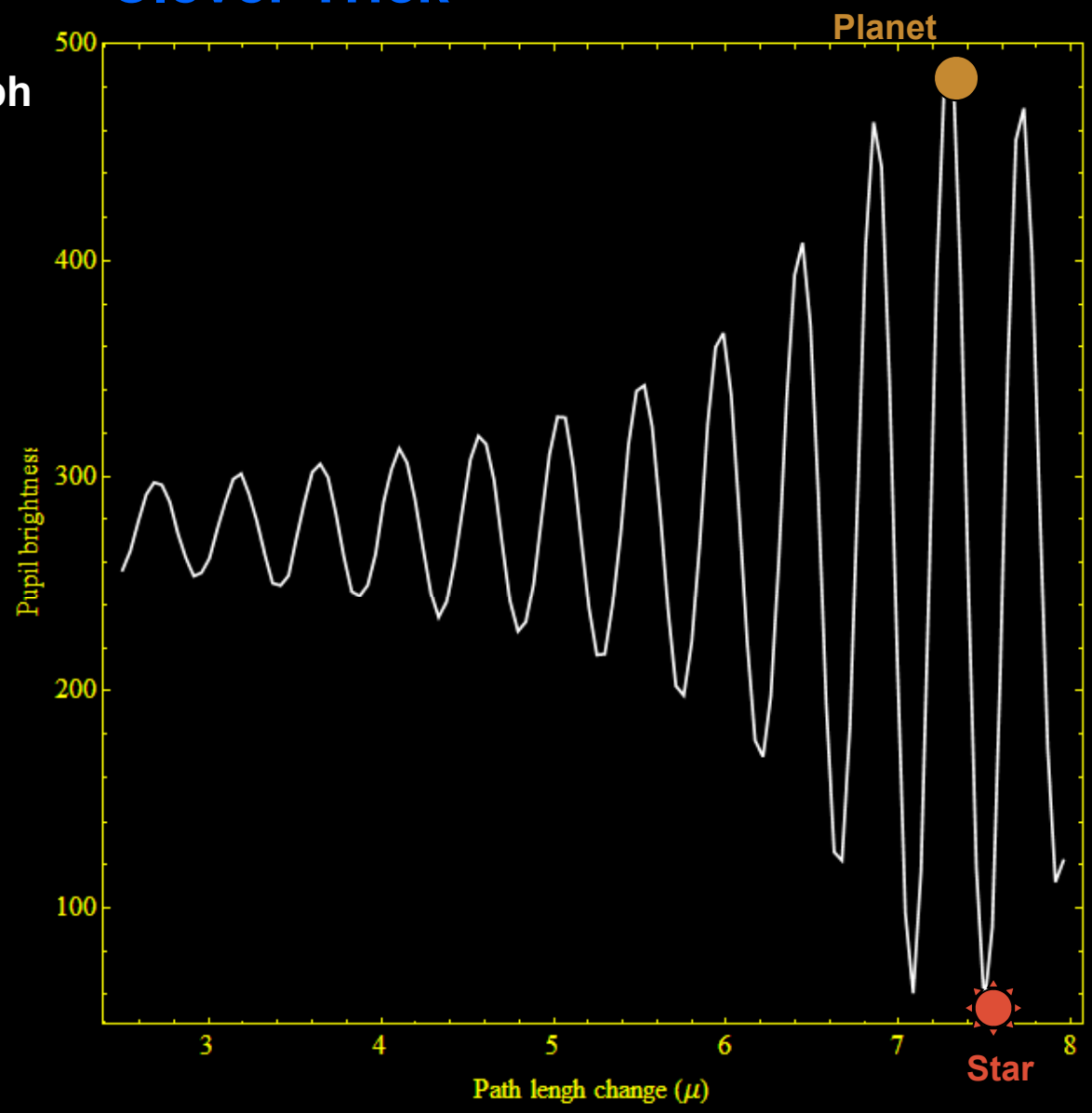
- **Visible Nulling Coronagraph**
  - White light interferometer
  - Deformable mirror

Nuller pupil



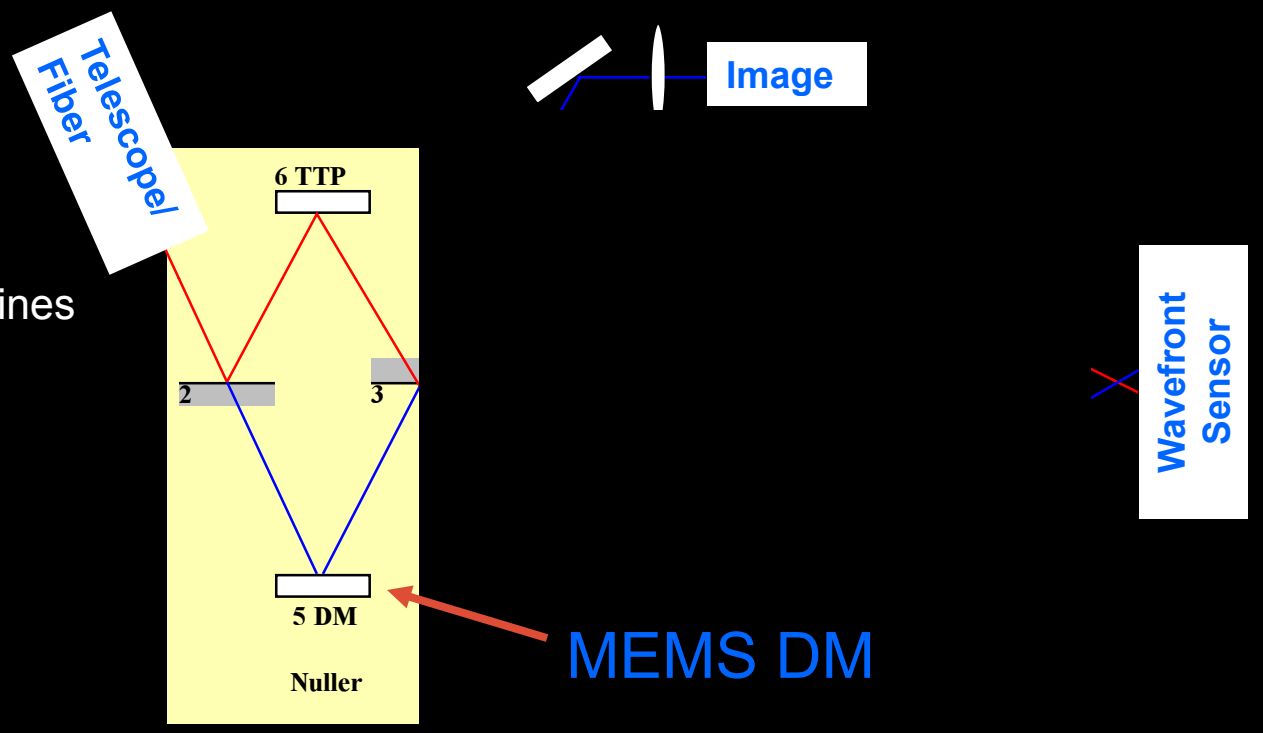
Clever Trick

- **Visible Nulling Coronagraph**
  - White light interferometer
  - Deformable mirror
- **Mach-Zender with shear**
  - Start at a dark fringe
  - Planet at a bright fringe
- **Tabletop demonstration**



Instrument

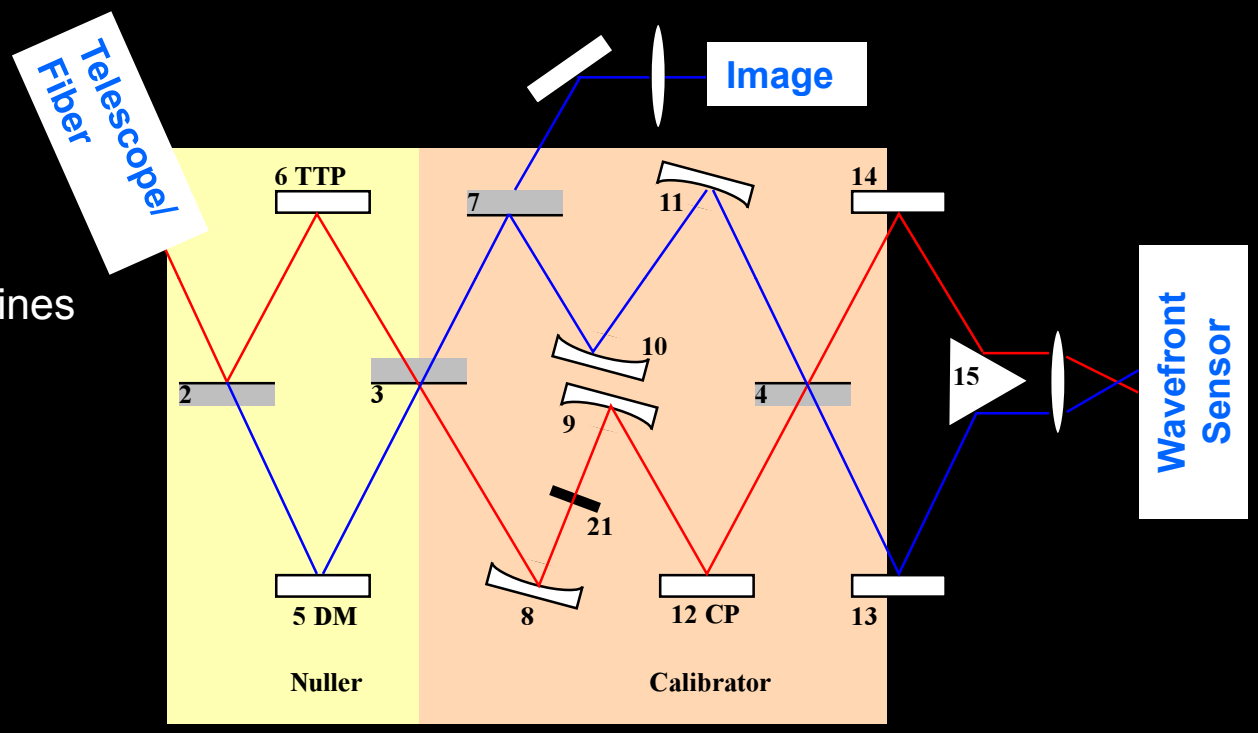
- **Telescope/Fiber**
- **Wavefront sensor**
- **Image sensor**
- **Nulling IFO**
  - Deformable mirror
  - 32x32 Boston Micromachines
  - Phase-shifting mirror
  - Tip/tilt/piston correction



IFO = Interferometer

Instrument

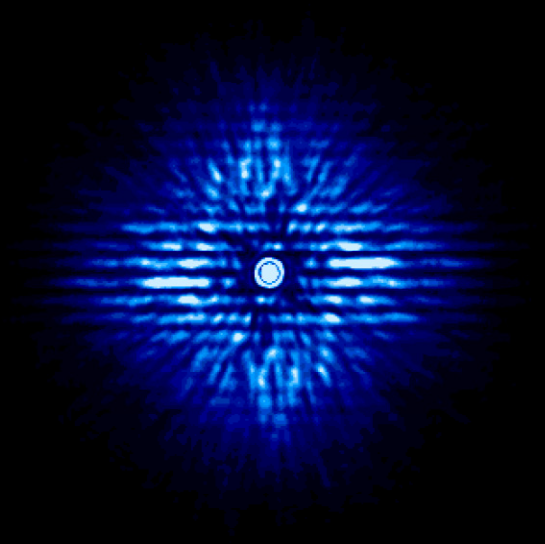
- **Telescope/Fiber**
- **Wavefront sensor**
- **Image sensor**
- **Nulling IFO**
  - Deformable mirror
  - 32x32 Boston Micromachines
  - Phase-shifting mirror
  - Tip/tilt/piston correction
- **Calibration IFO**
  - Phase-shifting mirror
  - Spatial filter



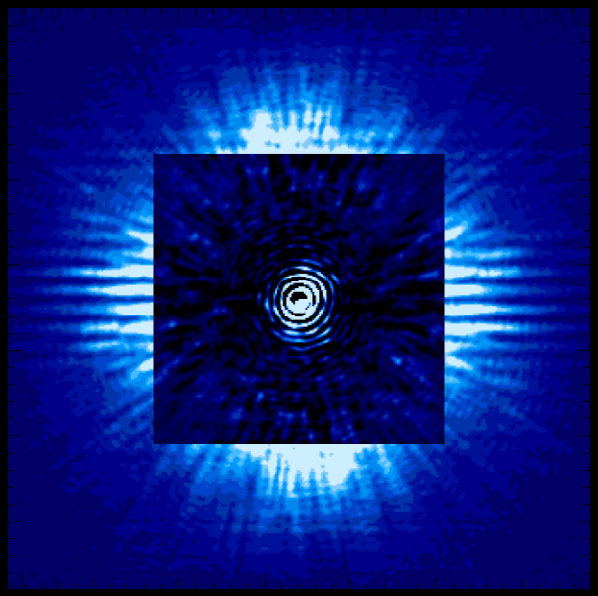
IFO = Interferometer

Strategy

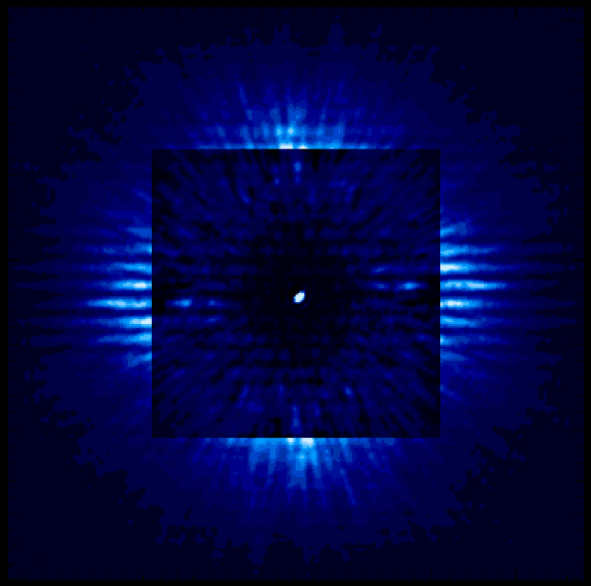
1. Alignment
2. Flatten the DM
3. Really flatten the DM
4. Post-process



After nulling



After calibration



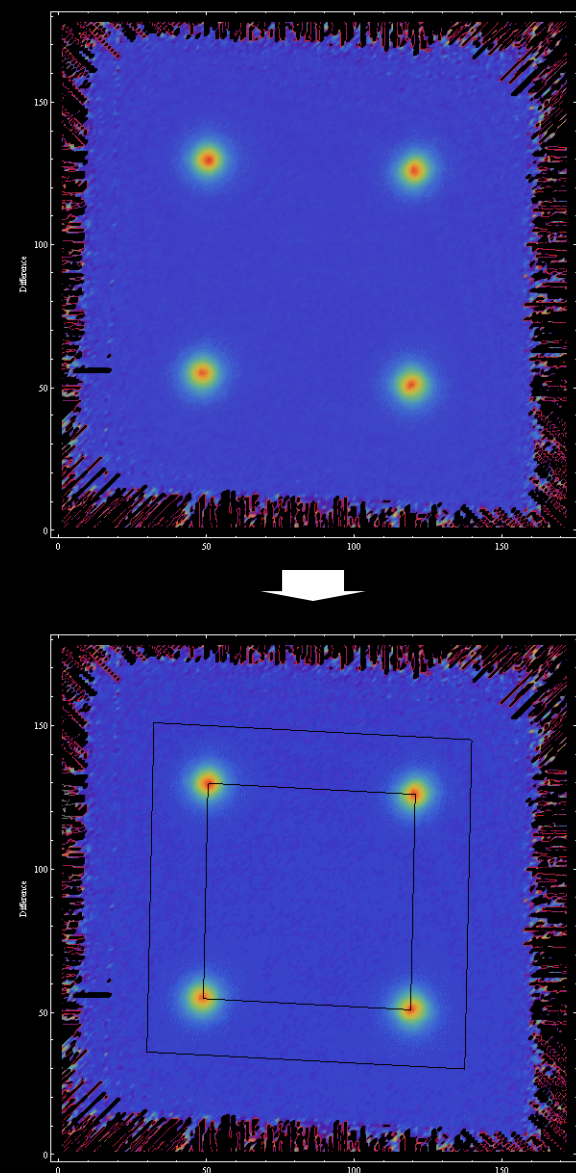
After image processing

Simulations by Ben Lane @ Draper

Operation I

1. Alignment

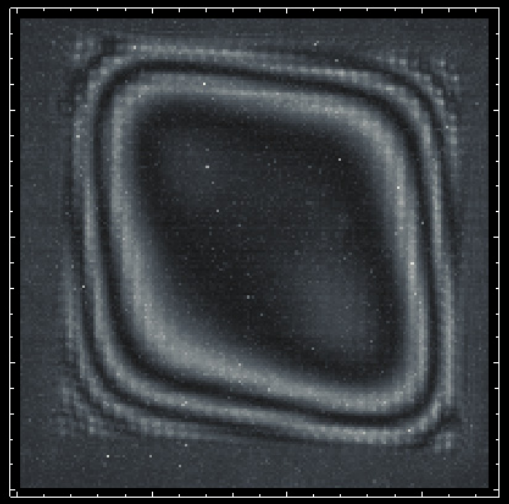
- Find the white light fringe
- Measure the phase
  ABCD = (0º, 90º, 180º, 270º)
- Move 4 actuators
- Measure the phase again
- Calculate the difference
- Calculate scaling, rotation, and skew



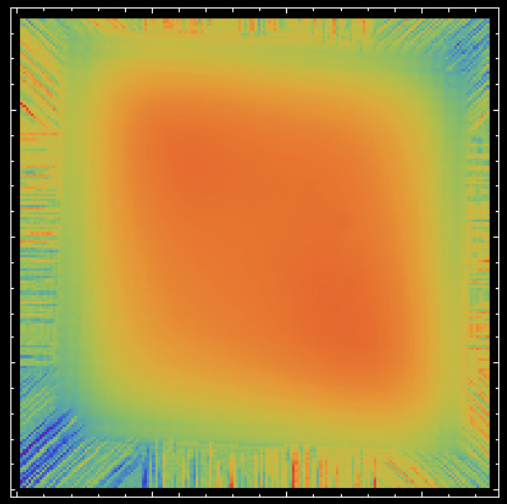
Operation II

2. Flatten the DM

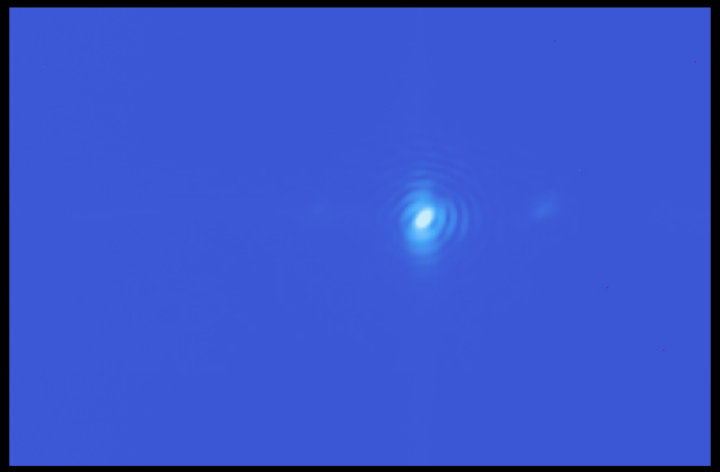
- Measure phase with
- 0º, 90º, 180º, 270º steps
- Feed back to TTP & DM



Interferogram



Unwrapped Phase



Coronagraph output image

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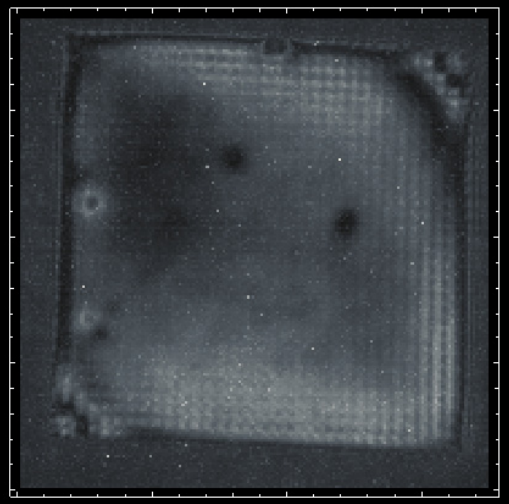
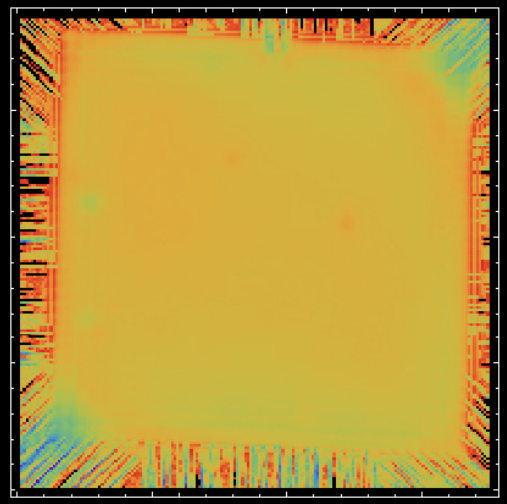


Interferogram



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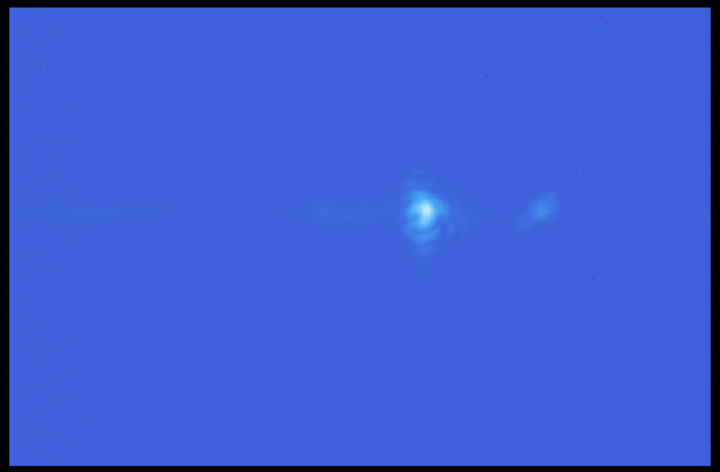

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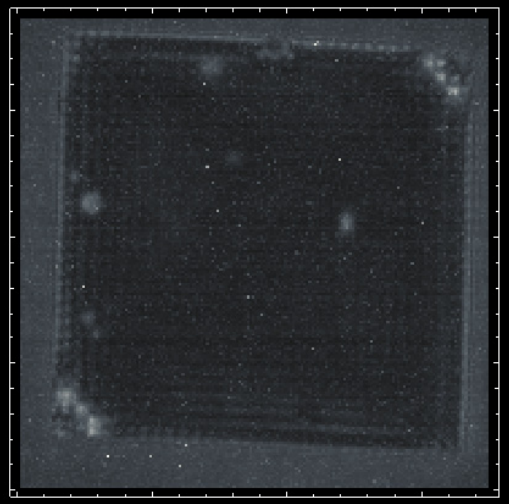

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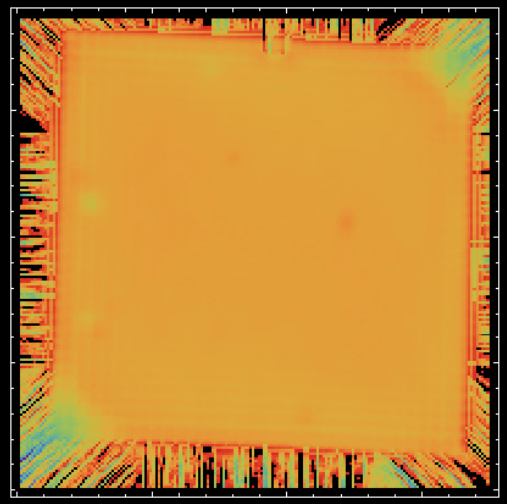

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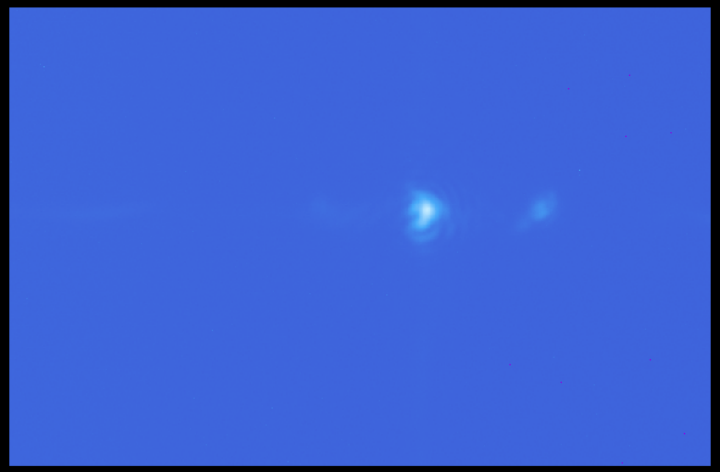

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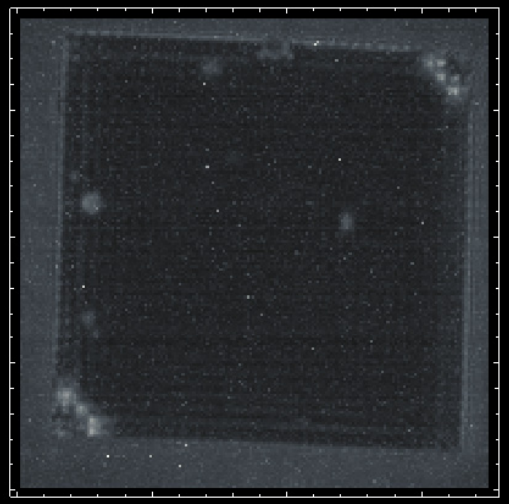
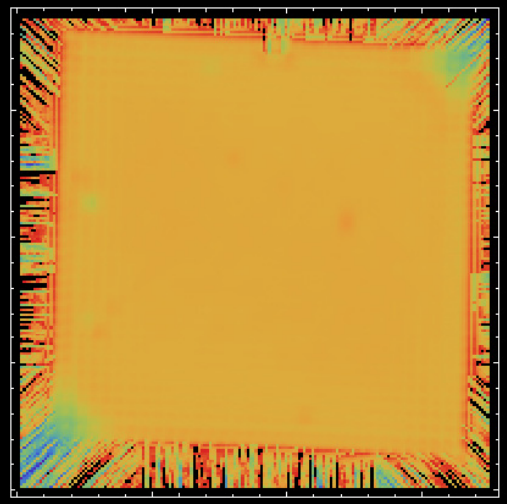
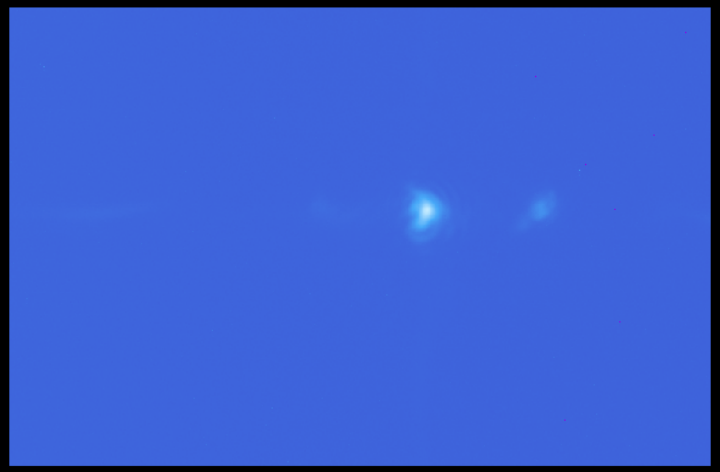


Interferogram



Unwrapped Phase



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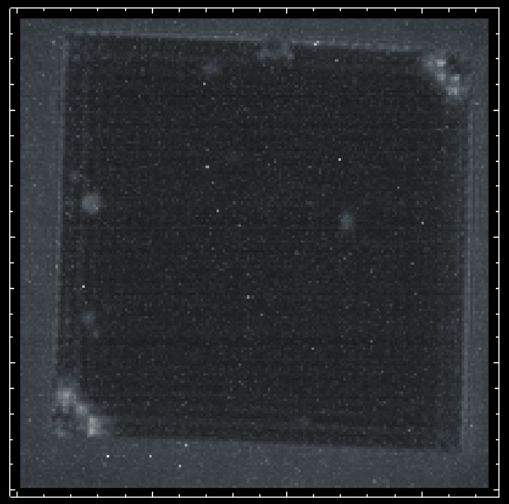
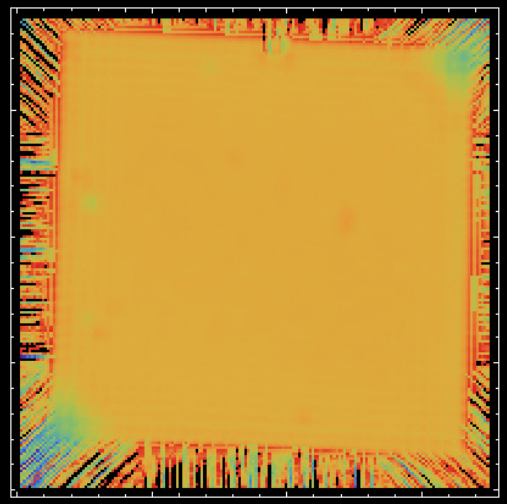


Interferogram



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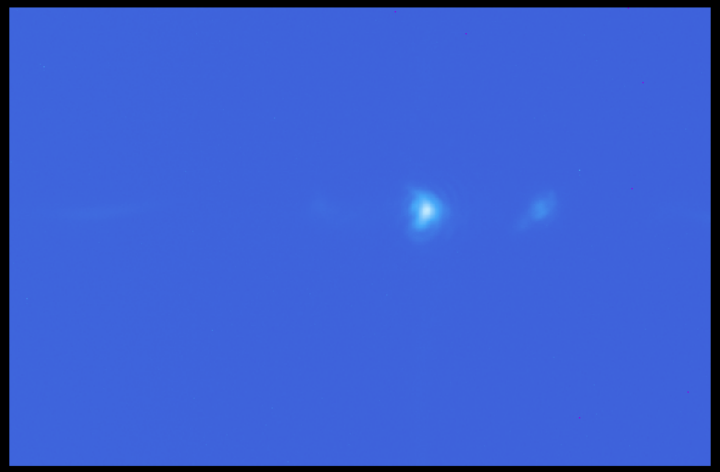

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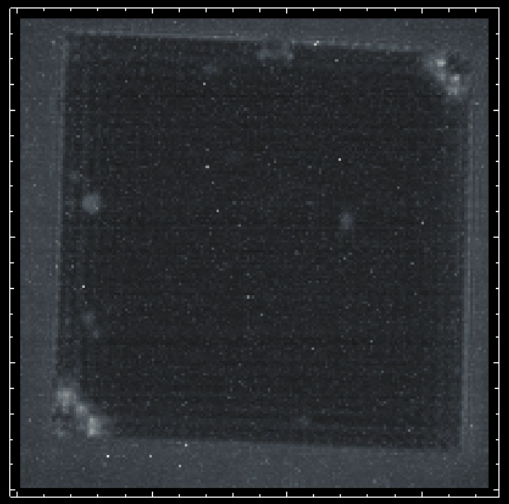

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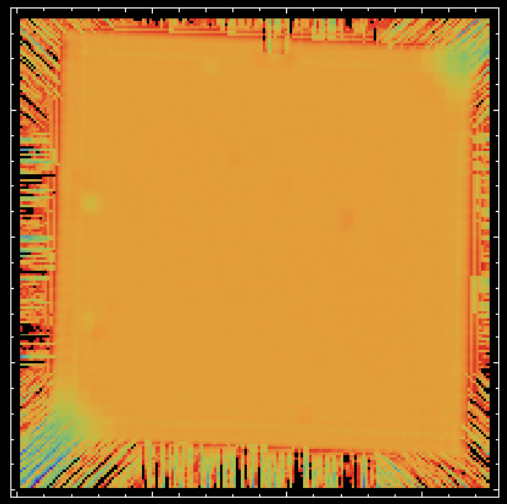

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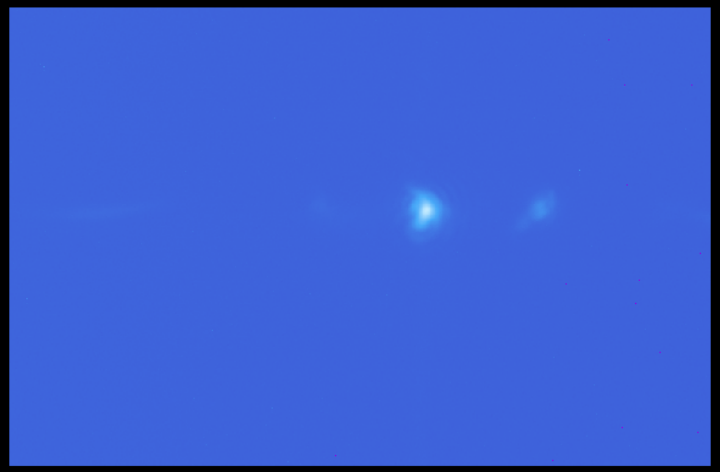

Coronagraph output image

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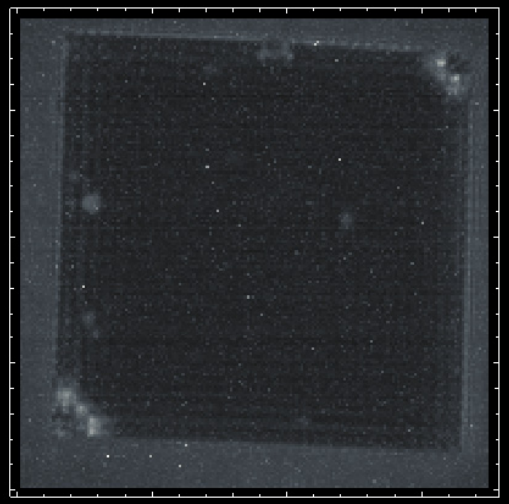

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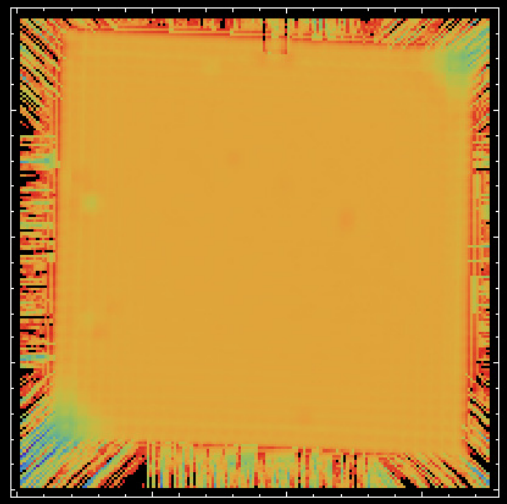
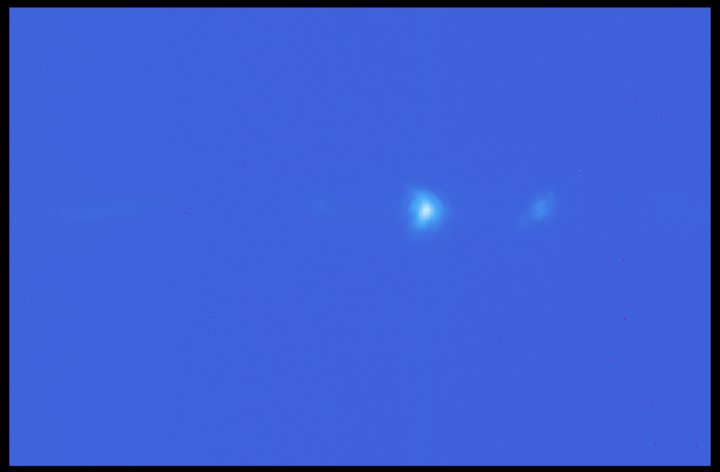


Unwrapped Phase

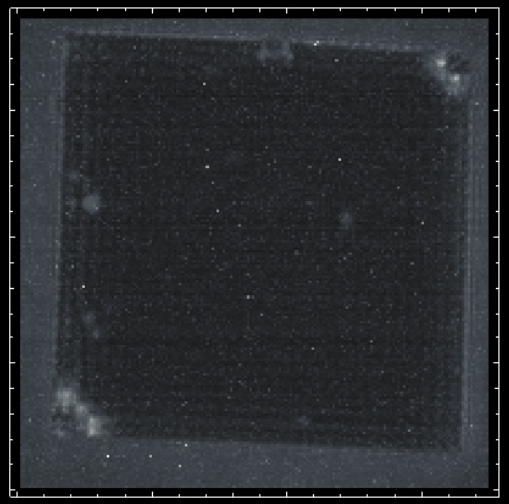


Coronagraph output image

Operation II

2. Flatten the DM

- Measure phase with
- 0º, 90º, 180º, 270º steps
- Feed back to TTP & DM
- Converges to 15nm rms



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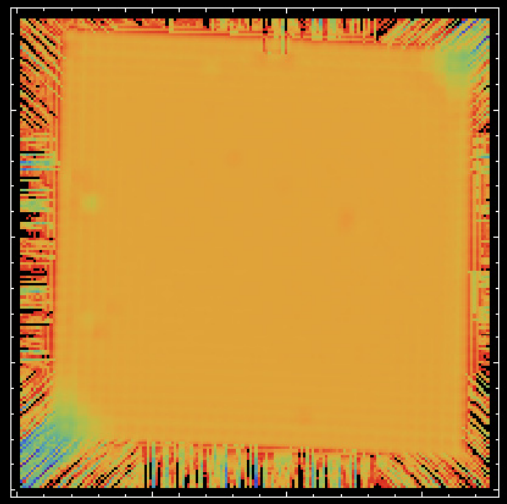
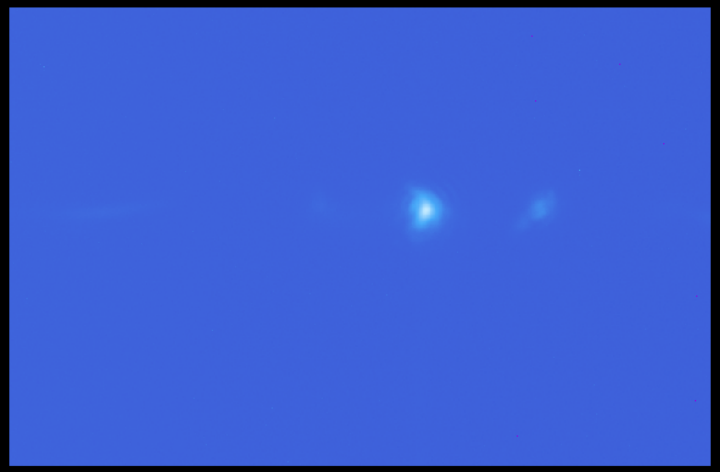


Unwrapped Phase



Coronagraph output image

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- Measure phase with
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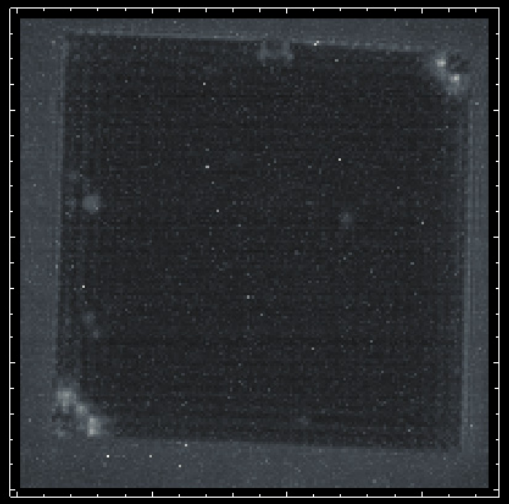

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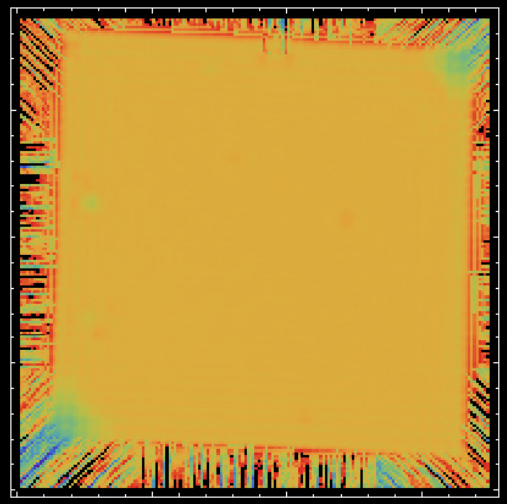
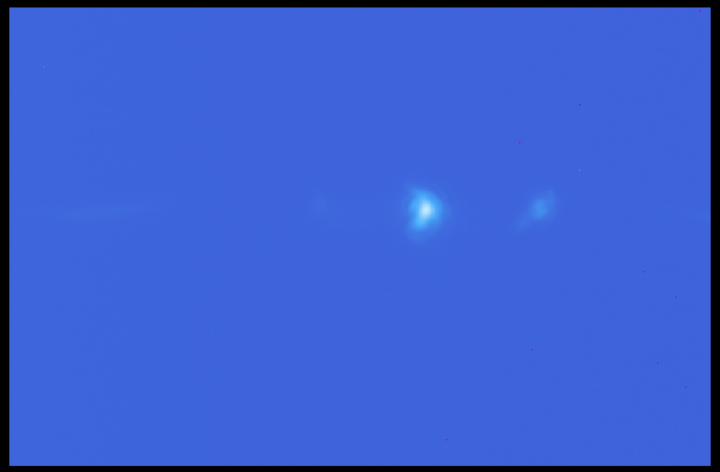


Unwrapped Phase

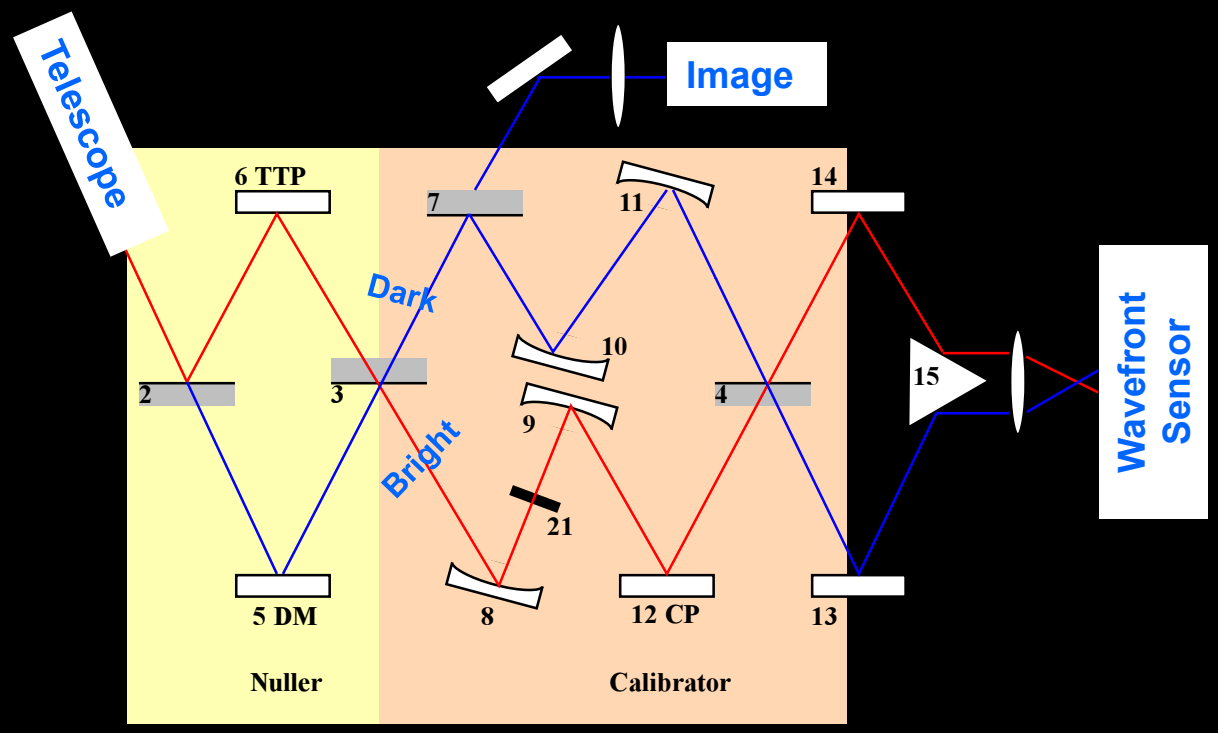


Coronagraph output image

Operation III

3. Really flatten the DM

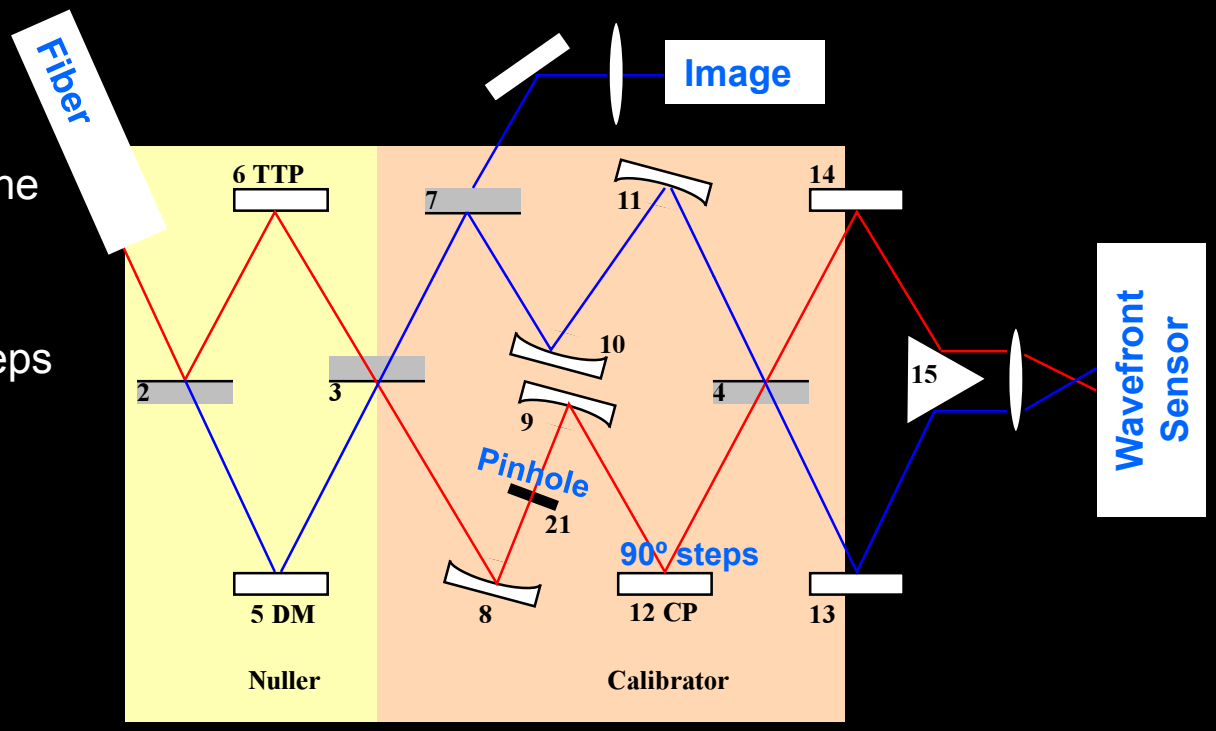
- The dark output contains suppressed starlight.
- Mix the nuller outputs.



Operation III

3. Really flatten the DM

- The dark output contains suppressed starlight.
- Mix the nuller outputs.
- A pinhole removes detail from the bright arm.
- Dither the nuller by 15nm
- 0º, 90º, 180º, 270º calibrator steps



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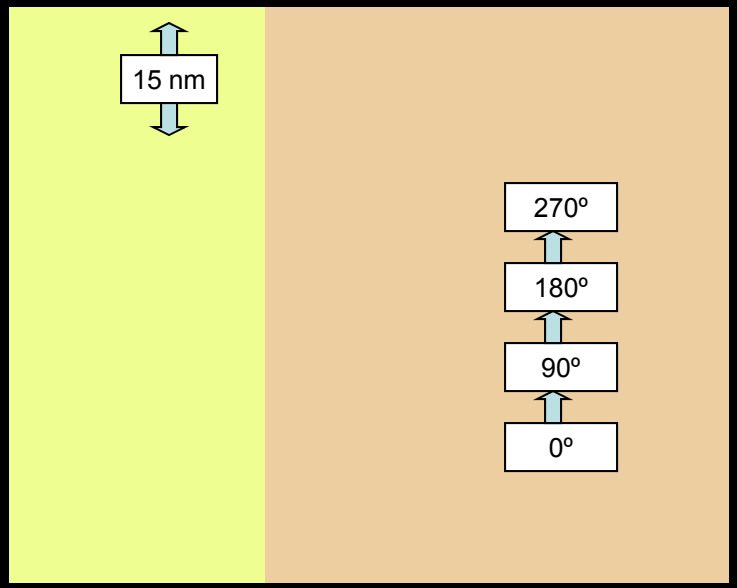
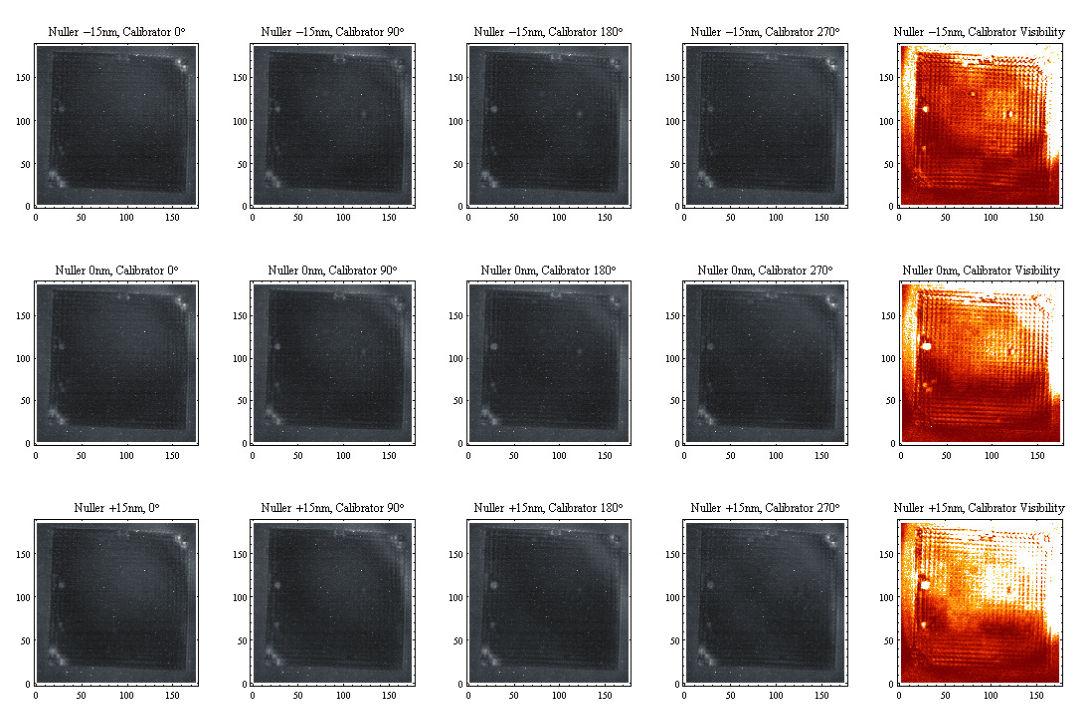


Operation III

3. Really flatten the DM

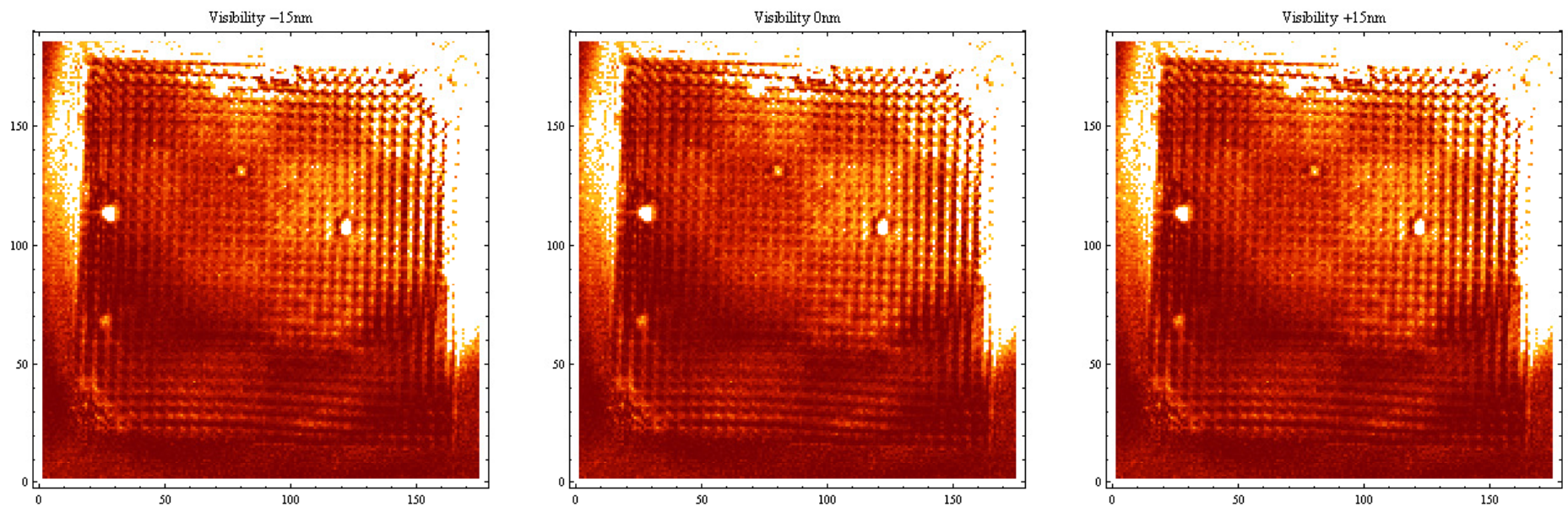
- The dark output contains suppressed starlight.
- Mix the nuller outputs.
- A pinhole removes detail from the bright arm.
- Dither the nuller by 15nm
- 0º, 90º, 180º, 270º calibrator steps
- 12 phase measurements

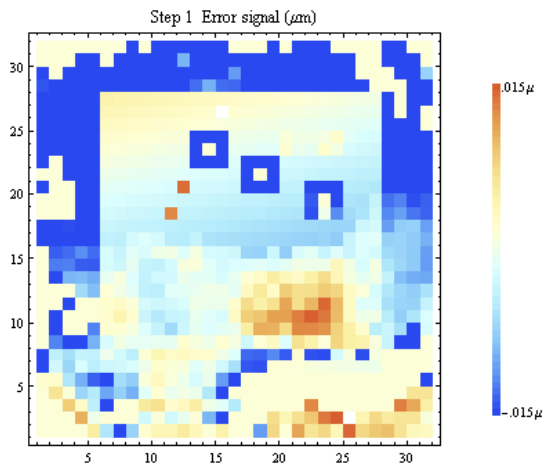


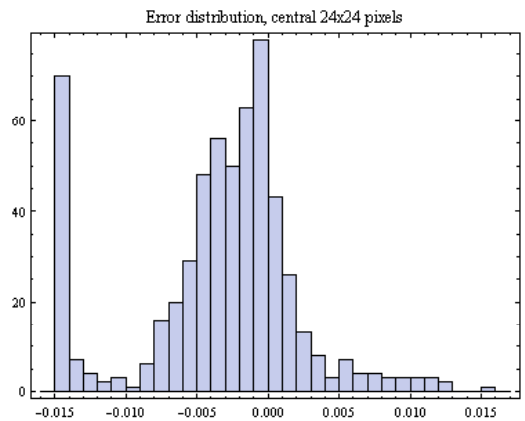
Operation III

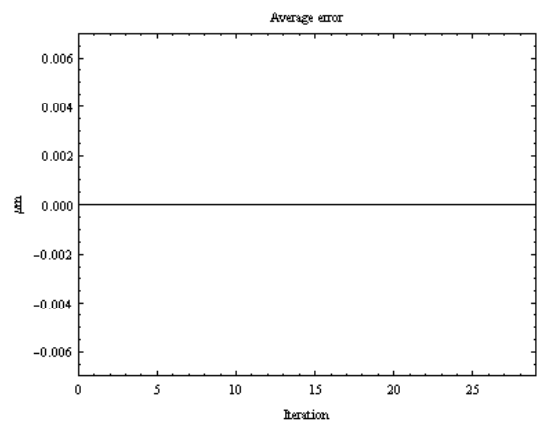
3. Really flatten the DM

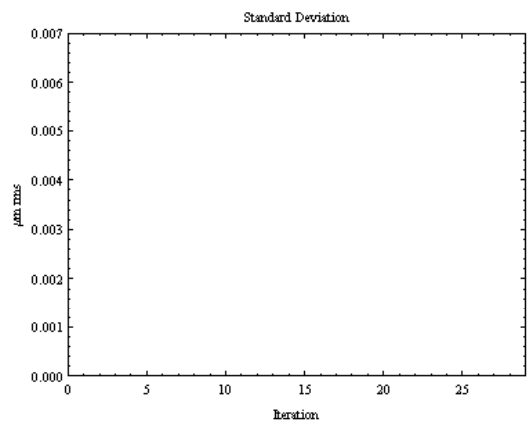
- Minimize visibility at the calibrator by varying the nuller phase
- Fit to a parabola, find the minimum
- Steadily decrease nuller step size
- Converges in ~10 iterations

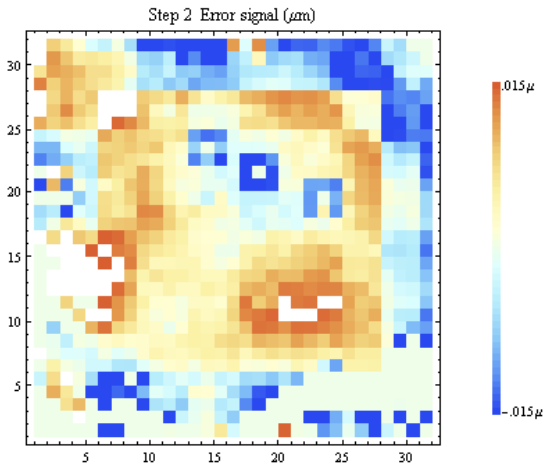


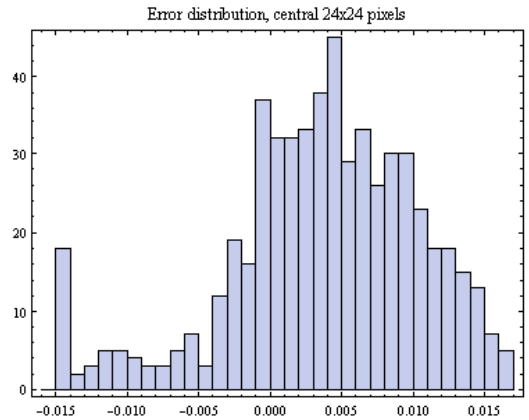

Step 1 Error signal (μm)
.015μ
-.015μ

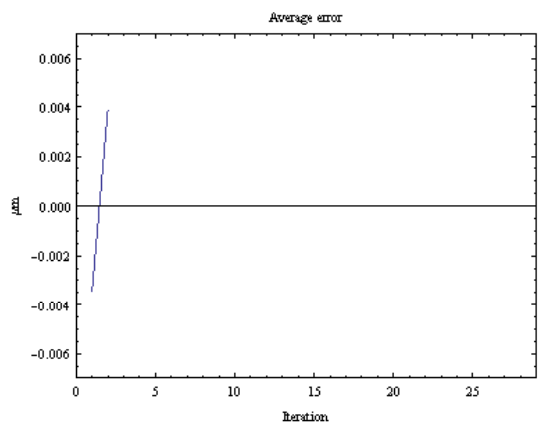

Error distribution, central 24x24 pixels

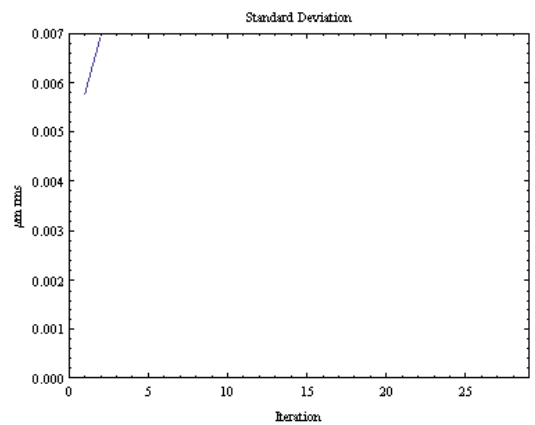

Average error
μm
Iteration

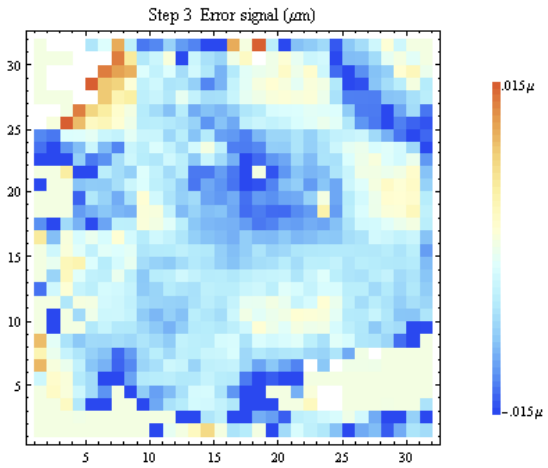

Standard Deviation
μm rms
Iteration

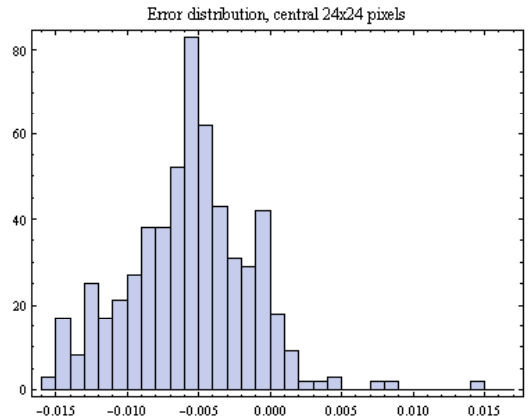

Step 2 Error signal (μm)
.015μ
-.015μ

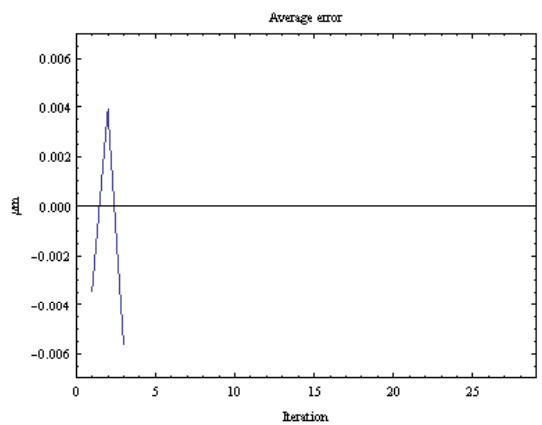

Error distribution, central 24x24 pixels

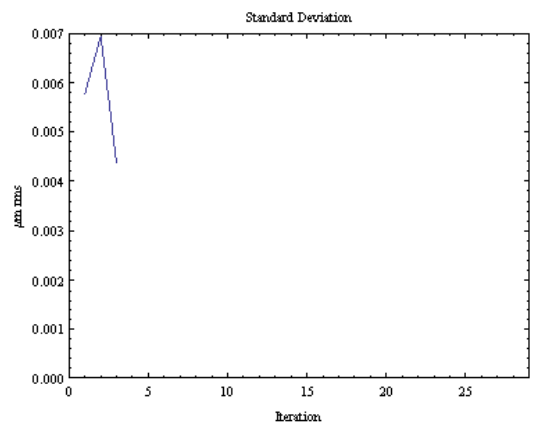

Average error
μm
Iteration

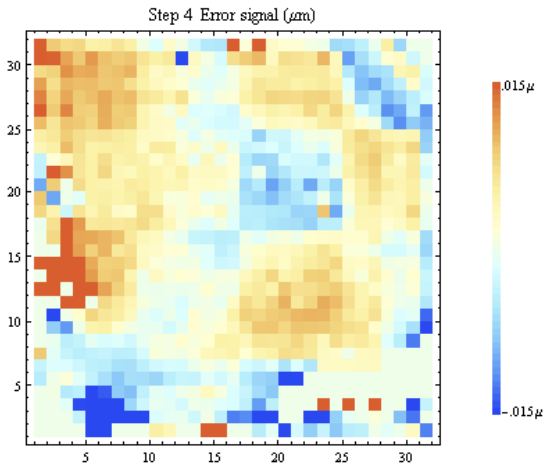

Standard Deviation
μm rms
Iteration

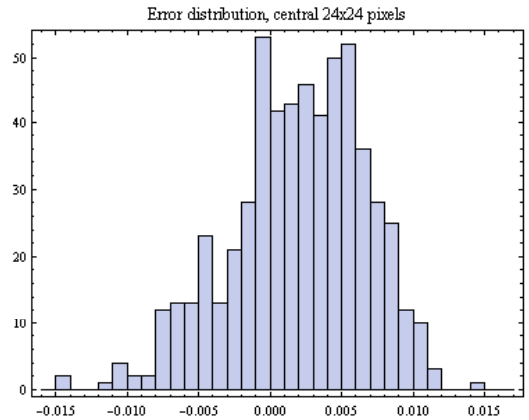

Step 3 Error signal (μm)
.015μ
-.015μ

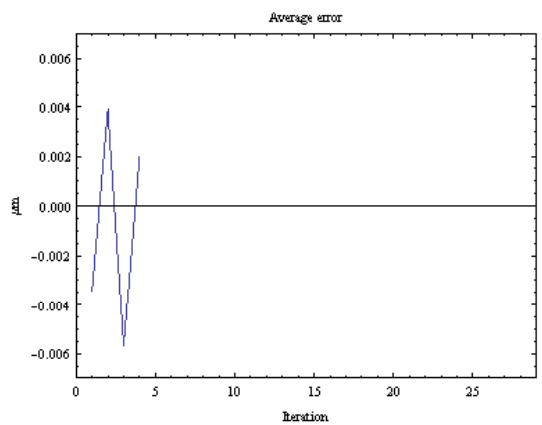

Error distribution, central 24x24 pixels

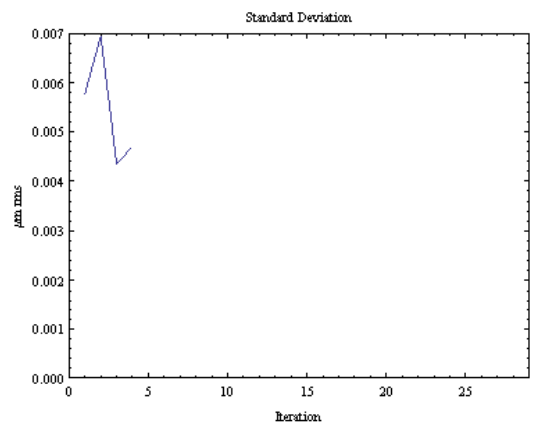

Average error
μm
Iteration

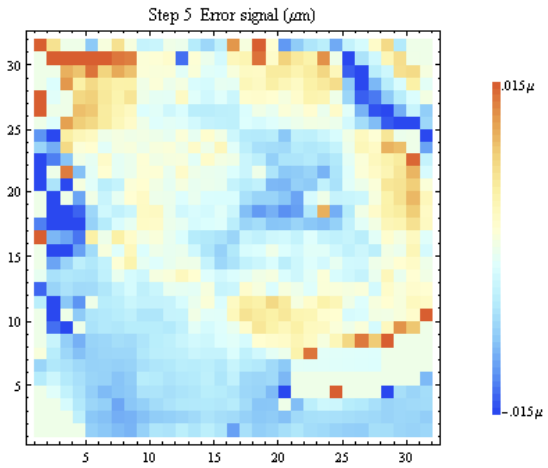

Standard Deviation
μm rms
Iteration

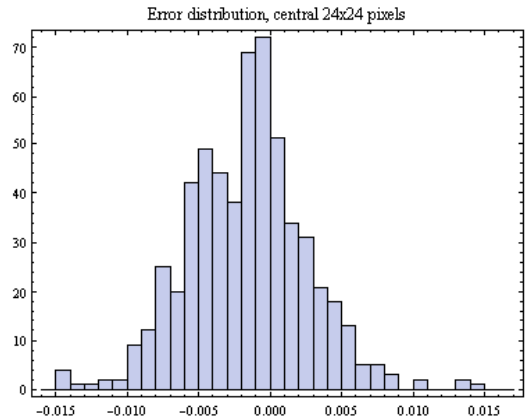

Step 4 Error signal (μm)
.015μ
-.015μ

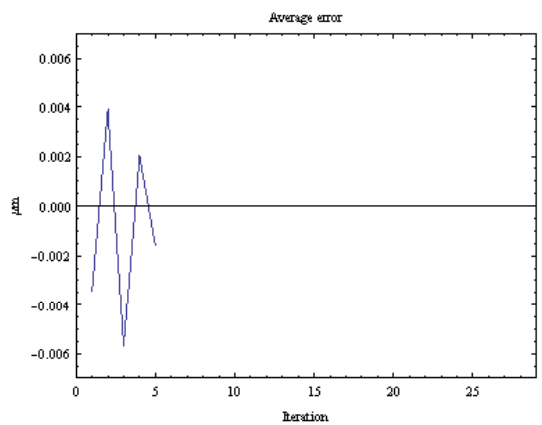

Error distribution, central 24x24 pixels

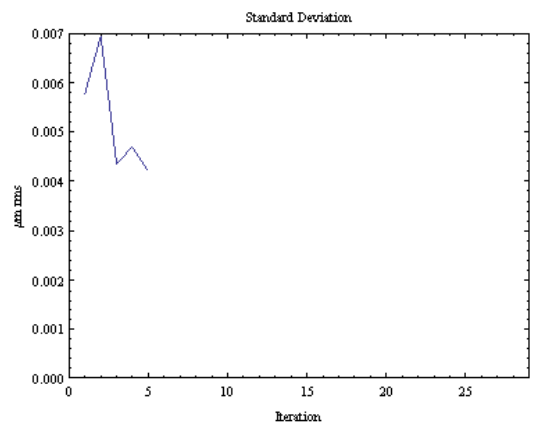

Average error
μm
Iteration

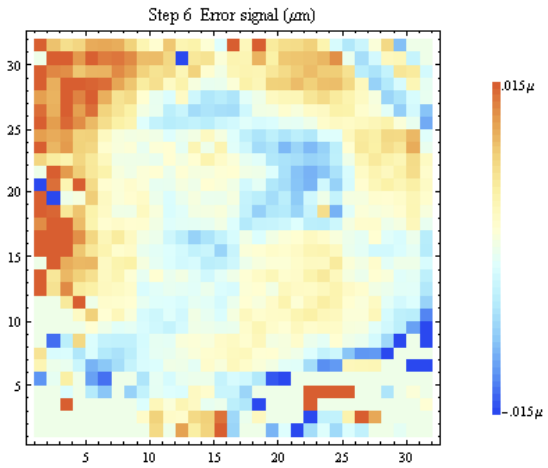

Standard Deviation
μm rms
Iteration

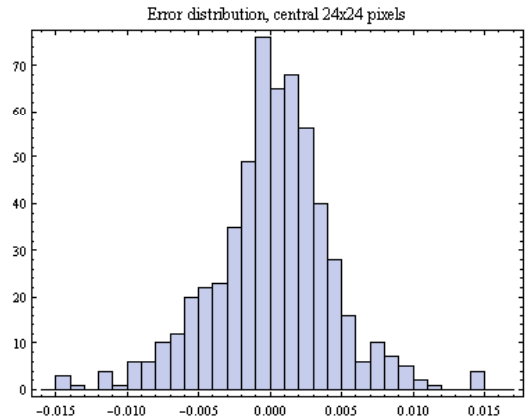

Step 5 Error signal (μm)
.015μ
-.015μ

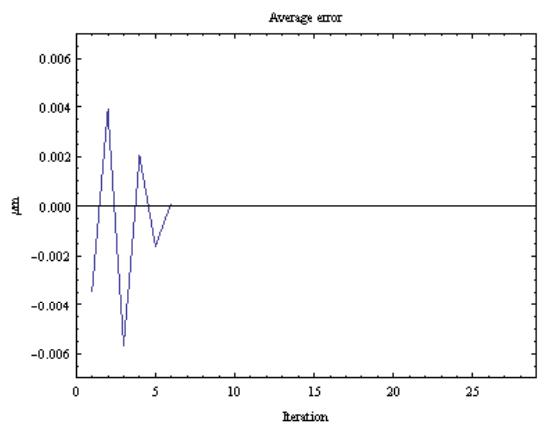

Error distribution, central 24x24 pixels

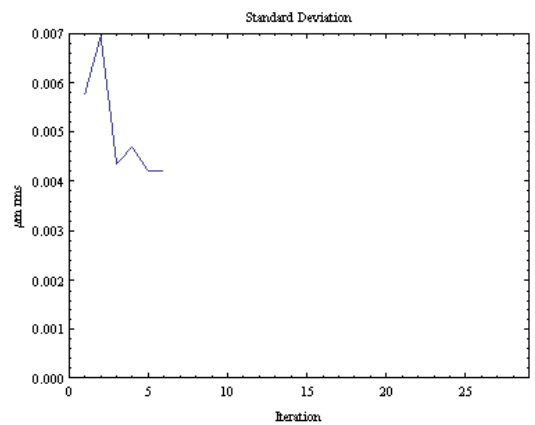

Average error
μm
Iteration

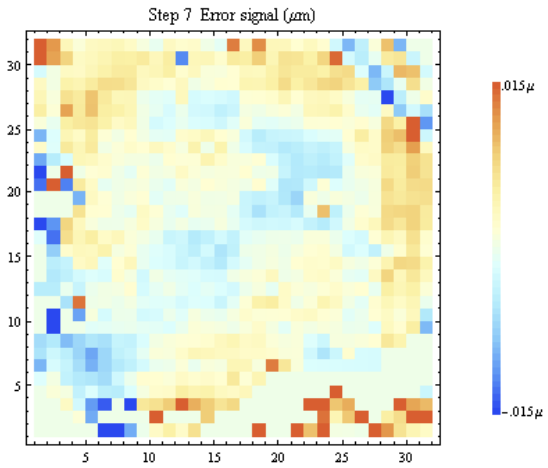

Standard Deviation
μm rms
Iteration

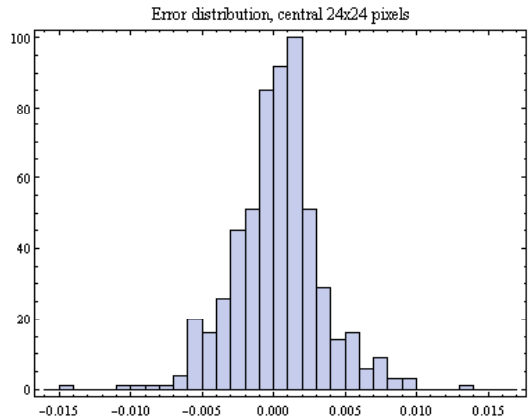

Step 6 Error signal (μm)
.015μ
-.015μ

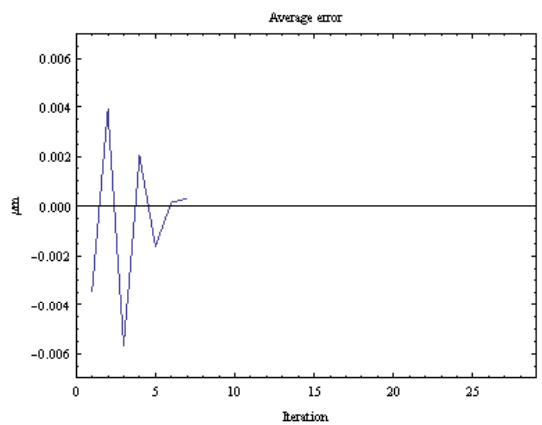

Error distribution, central 24x24 pixels

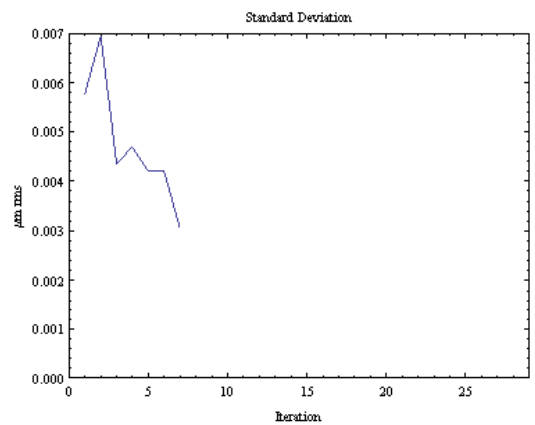

Average error
μm
Iteration

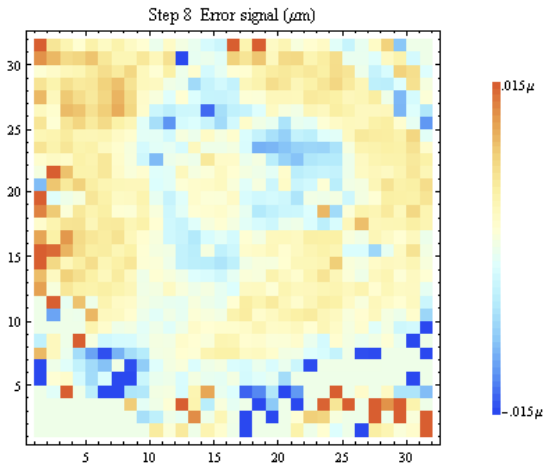

Standard Deviation
μm rms
Iteration

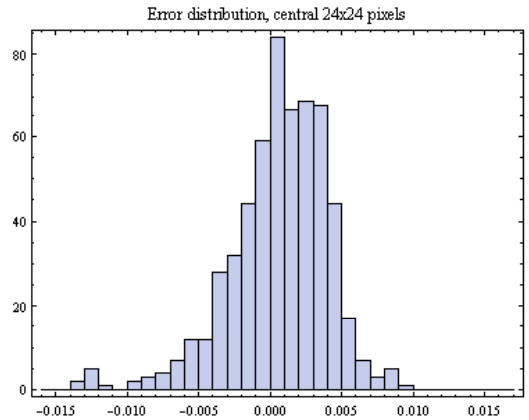

Step 7 Error signal (μm)
.015μ
-.015μ

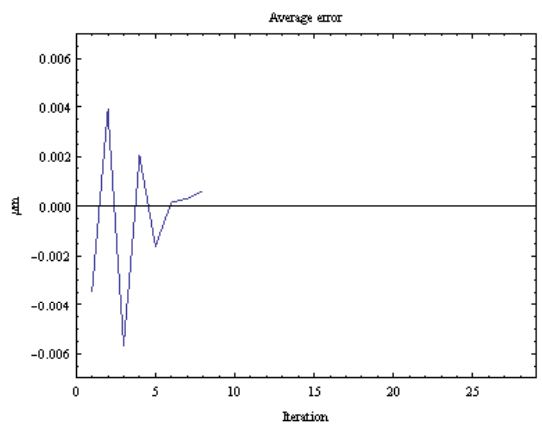

Error distribution, central 24x24 pixels

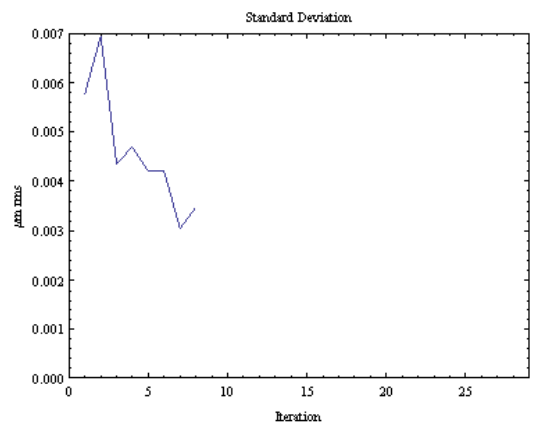

Average error
μm
Iteration

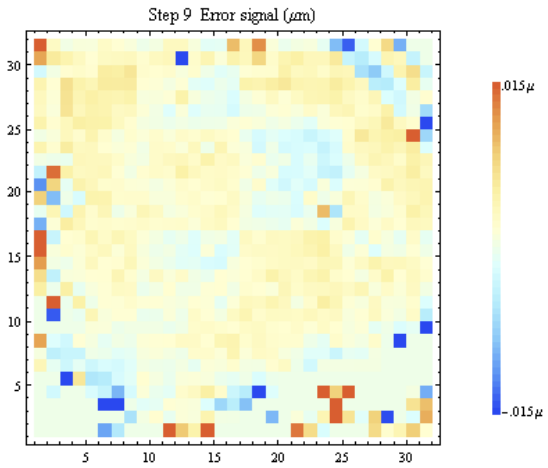

Standard Deviation
μm rms
Iteration

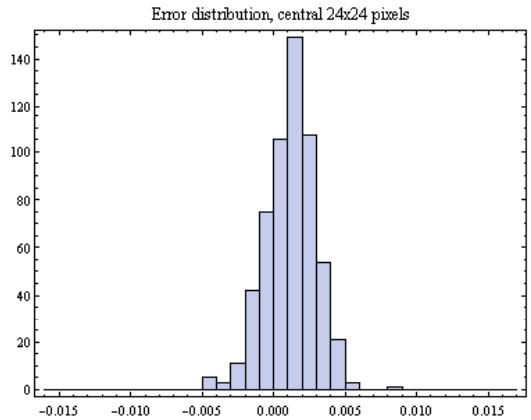

Step 8 Error signal (μm)
.015μ
-.015μ

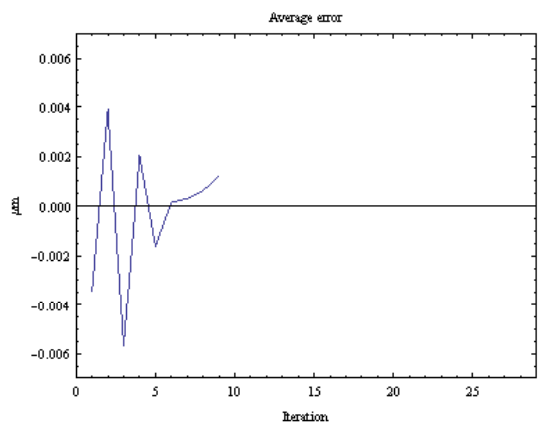

Error distribution, central 24x24 pixels

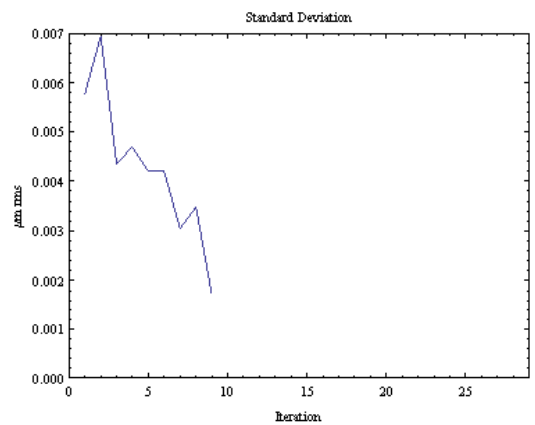

Average error
μm
Iteration

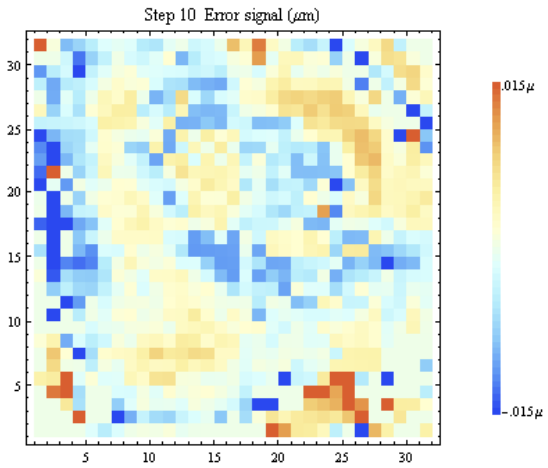

Standard Deviation
μm rms
Iteration

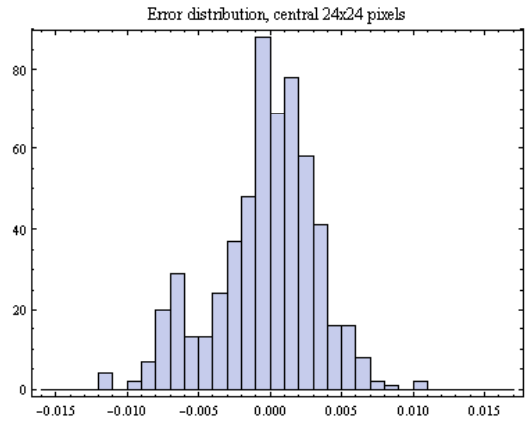

Step 9 Error signal (μm)
.015μ
-.015μ

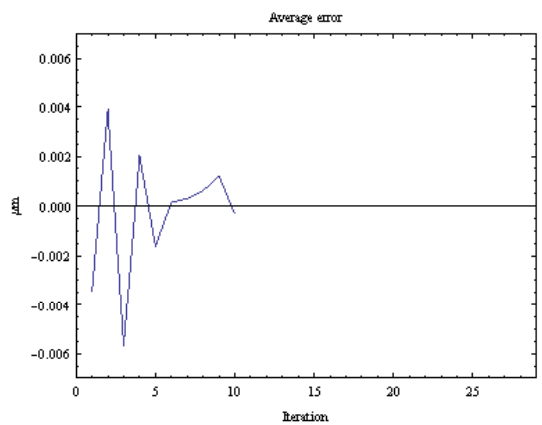

Error distribution, central 24x24 pixels

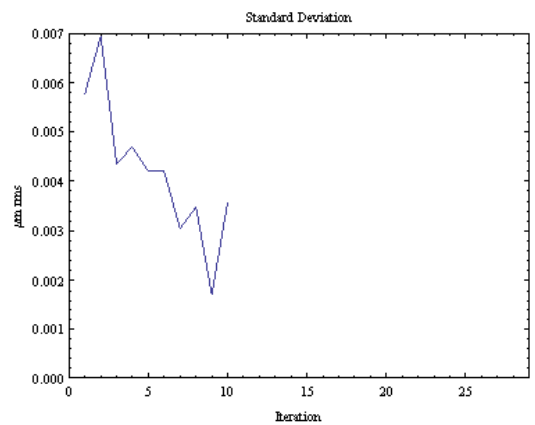

Average error
μm
Iteration

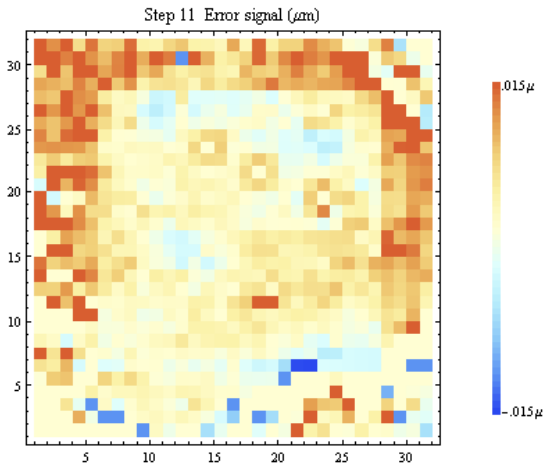

Standard Deviation
μm rms
Iteration

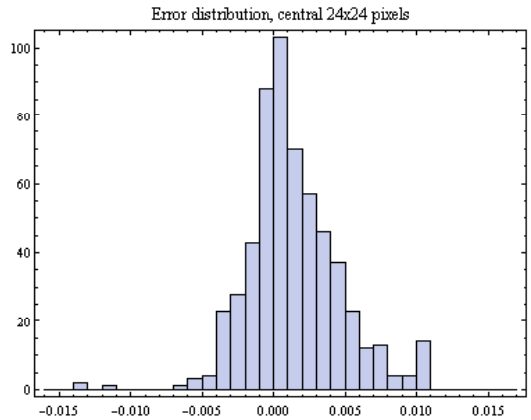

Step 10 Error signal (μm)
.015μ
-.015μ

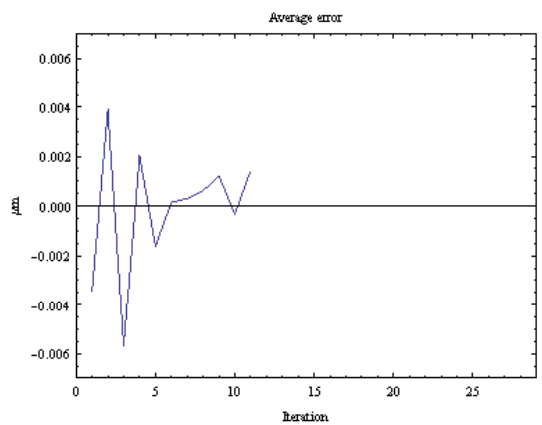

Error distribution, central 24x24 pixels

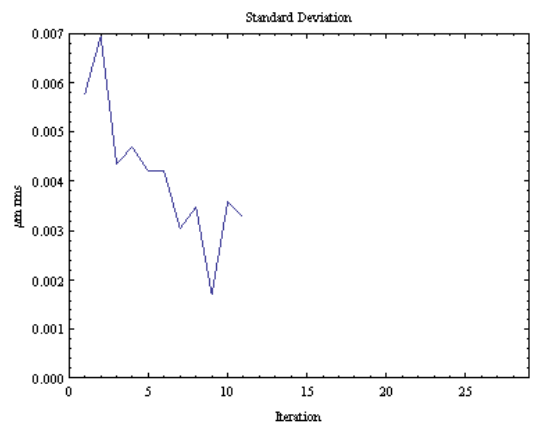

Average error
μm
Iteration

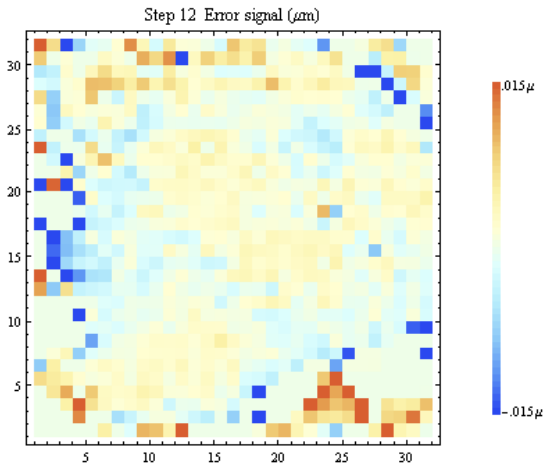

Standard Deviation
μm rms
Iteration

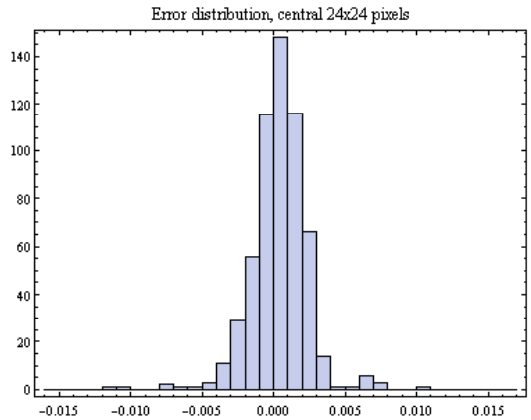

Step 11 Error signal (μm)
.015μ
-.015μ

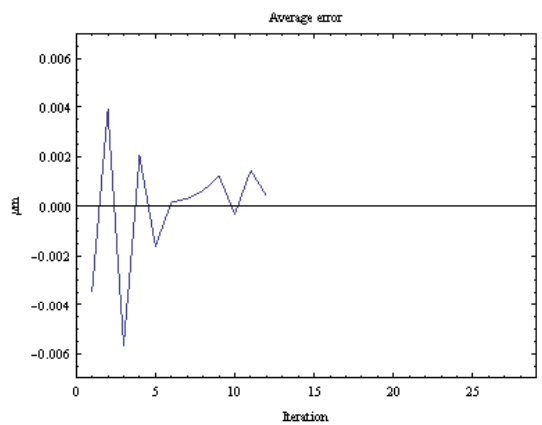

Error distribution, central 24x24 pixels

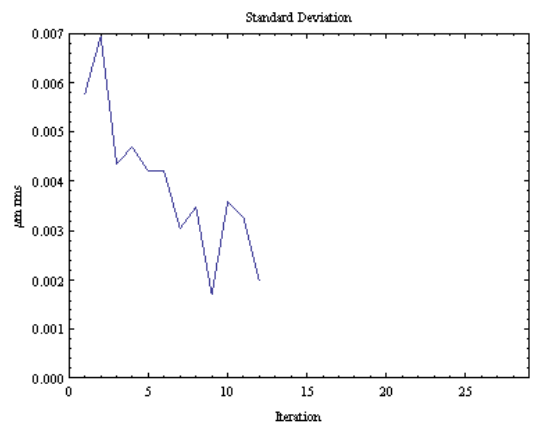

Average error
μm
Iteration

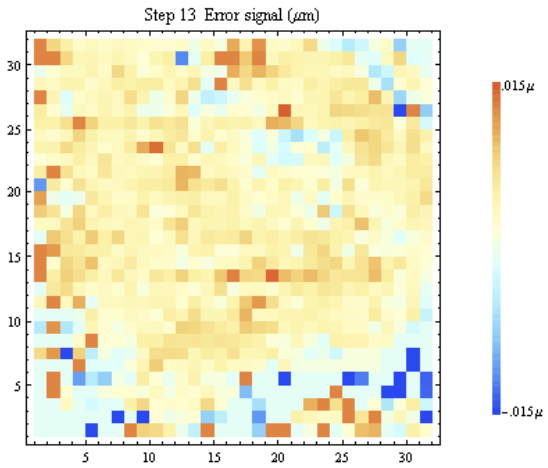

Standard Deviation
μm rms
Iteration

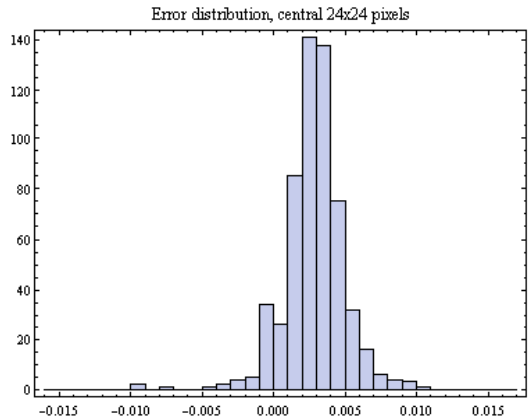

Step 12 Error signal (μm)
.015μ
-.015μ

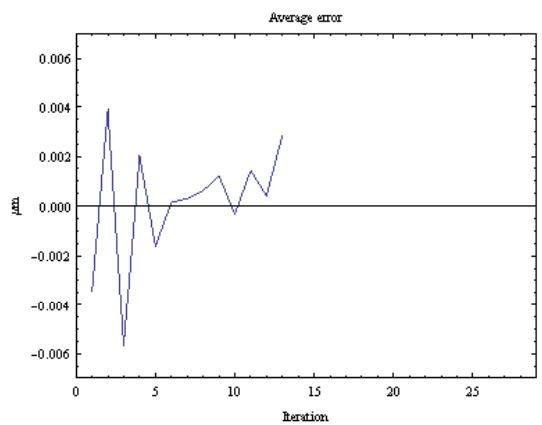

Error distribution, central 24x24 pixels

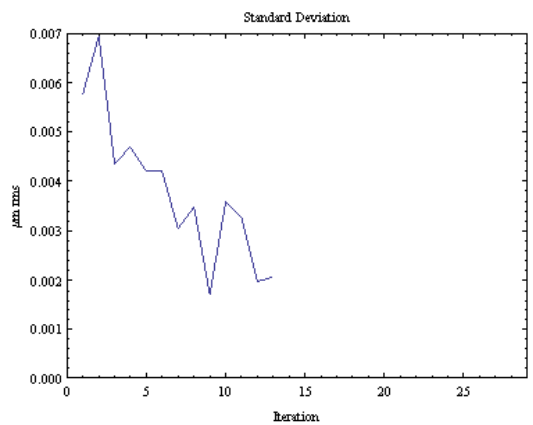

Average error
μm
Iteration

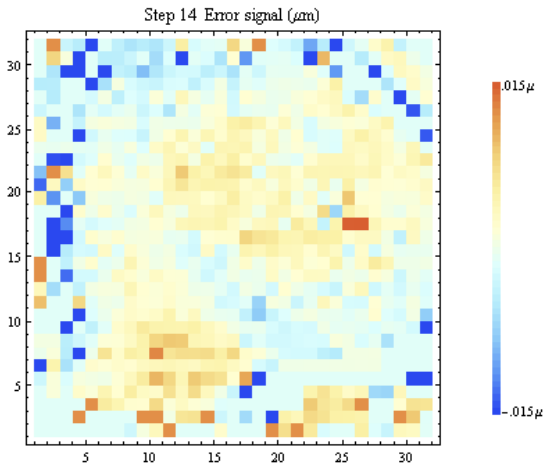

Standard Deviation
μm rms
Iteration

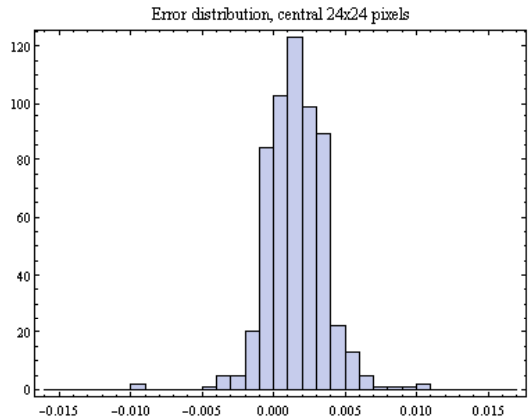

Step 13 Error signal (μm)
.015μ
-.015μ

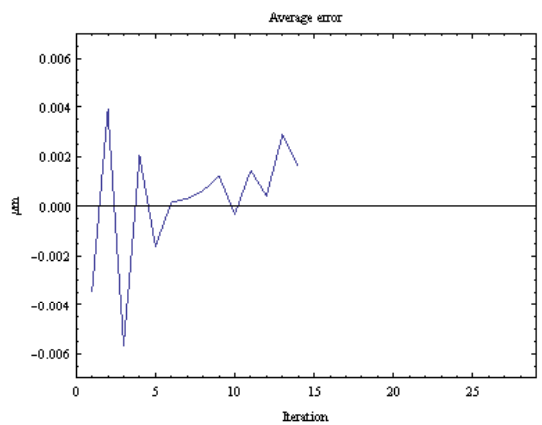

Error distribution, central 24x24 pixels

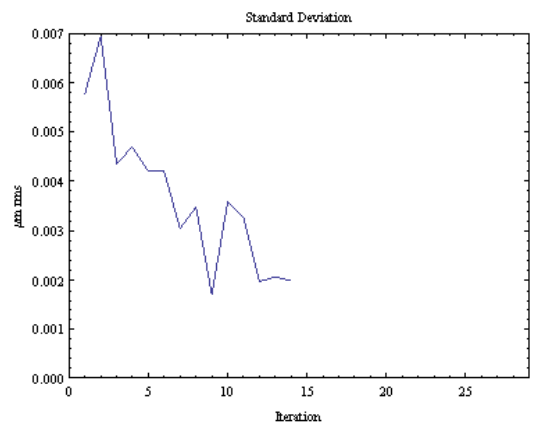

Average error
μm
Iteration

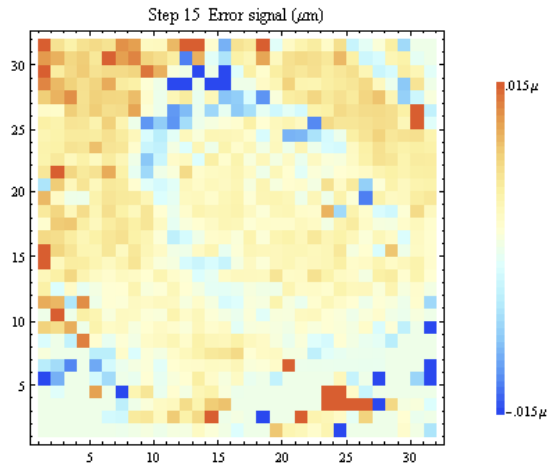

Standard Deviation
μm rms
Iteration

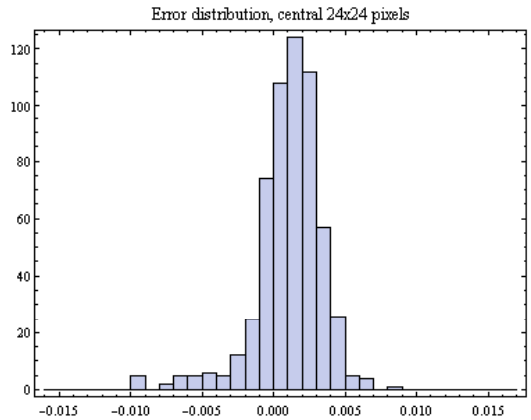

Step 14 Error signal (μm)
.015μ
-.015μ

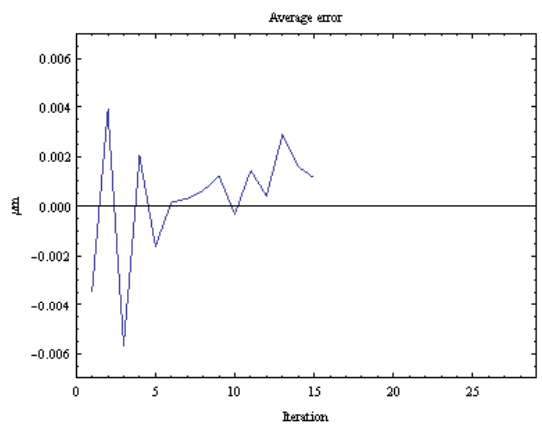

Error distribution, central 24x24 pixels

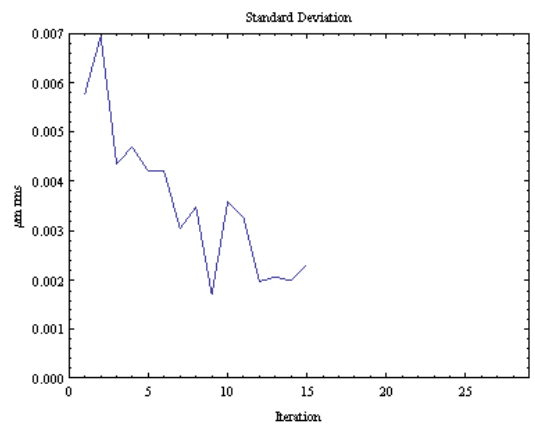

Average error
μm
Iteration

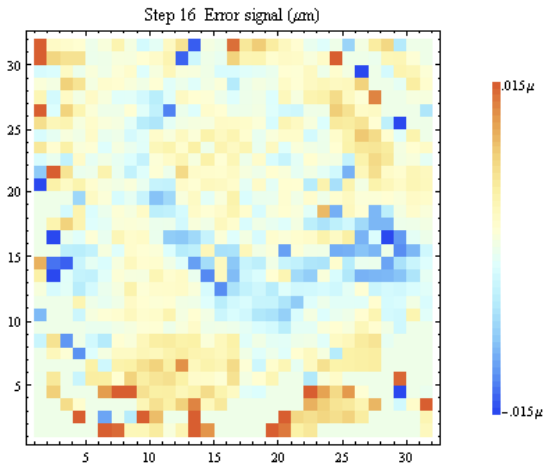

Standard Deviation
μm rms
Iteration

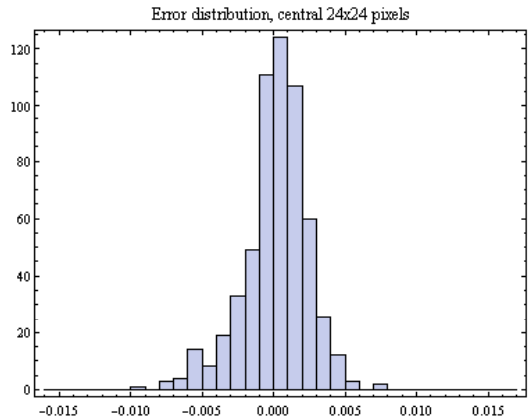

Step 15 Error signal (μm)
.015μ
-.015μ

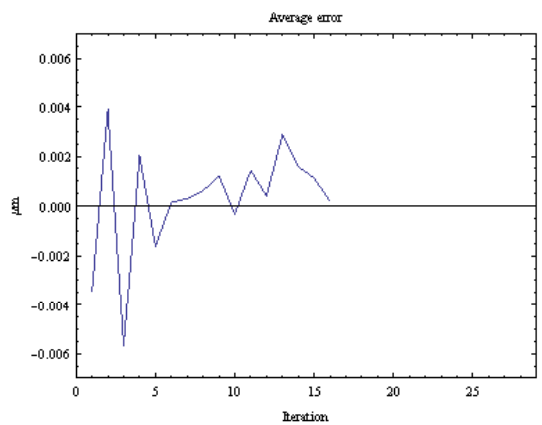

Error distribution, central 24x24 pixels

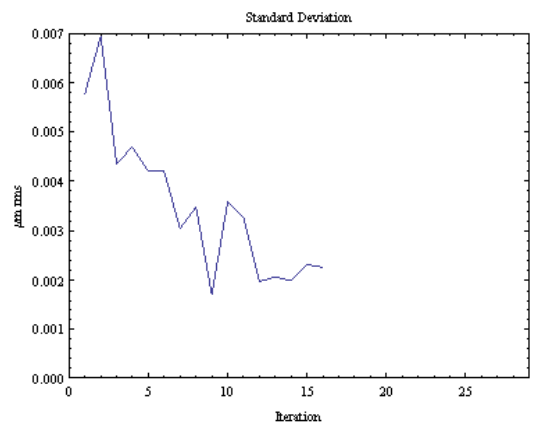

Average error
μm
Iteration

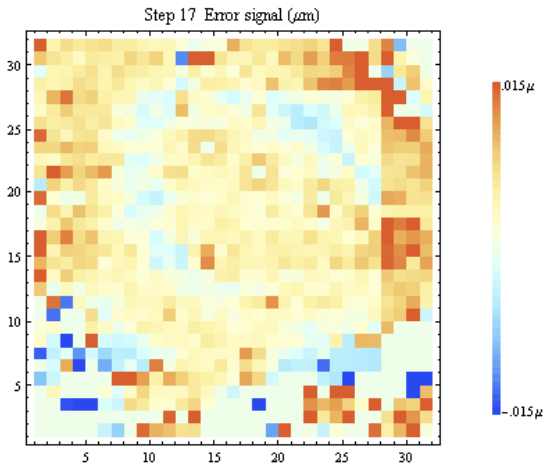

Standard Deviation
μm rms
Iteration

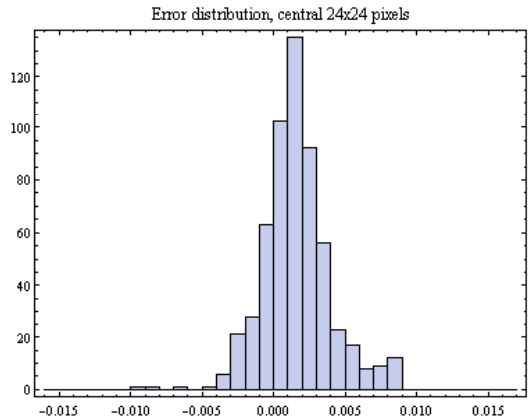

Step 16 Error signal (μm)
.015μ
-.015μ

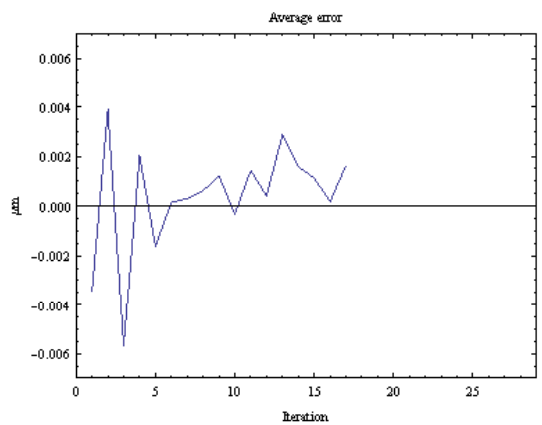

Error distribution, central 24x24 pixels

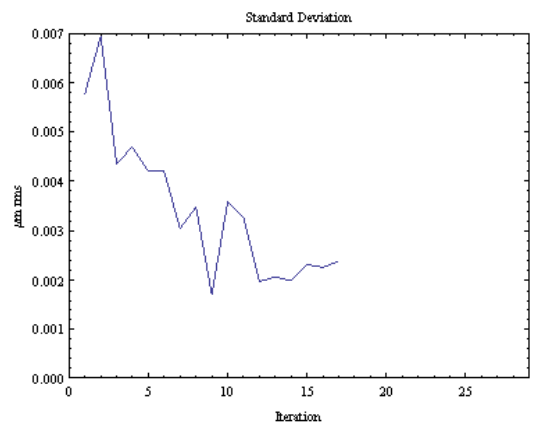

Average error
μm
Iteration

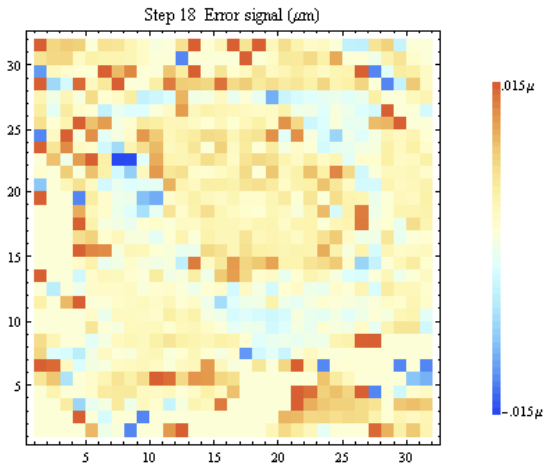

Standard Deviation
μm rms
Iteration

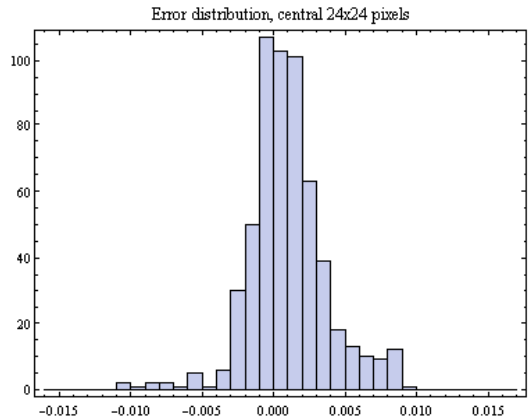

Step 17 Error signal (μm)
.015μ
-.015μ

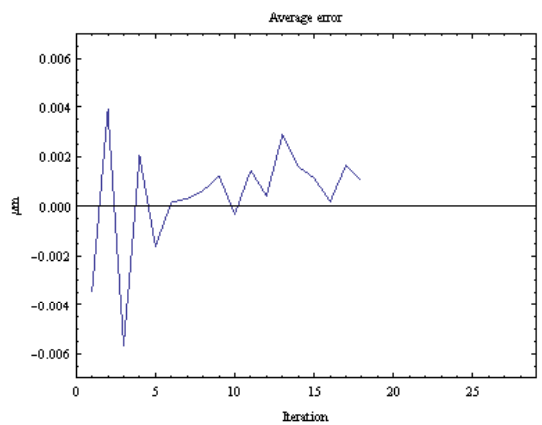

Error distribution, central 24x24 pixels

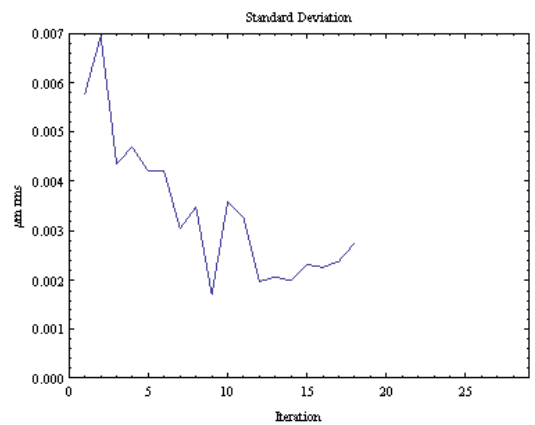

Average error
μm
Iteration

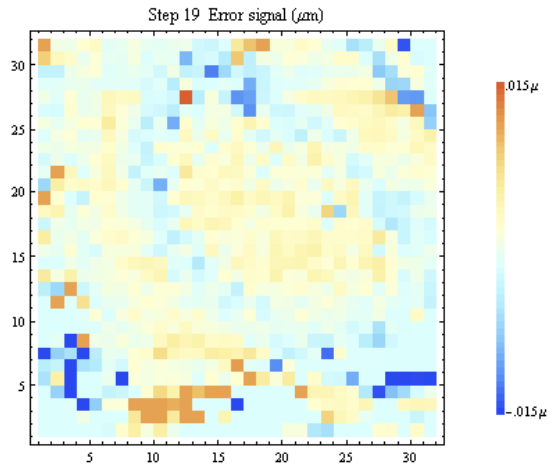

Standard Deviation
μm rms
Iteration

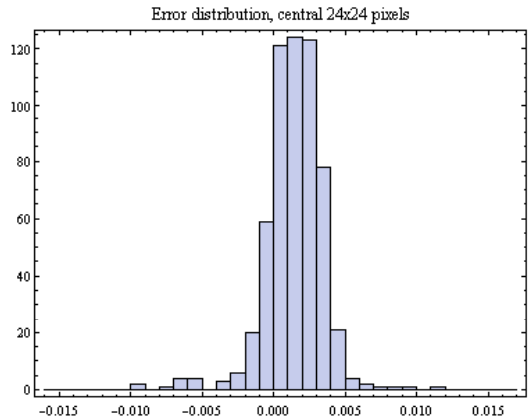

Step 18 Error signal (μm)
.015μ
-.015μ

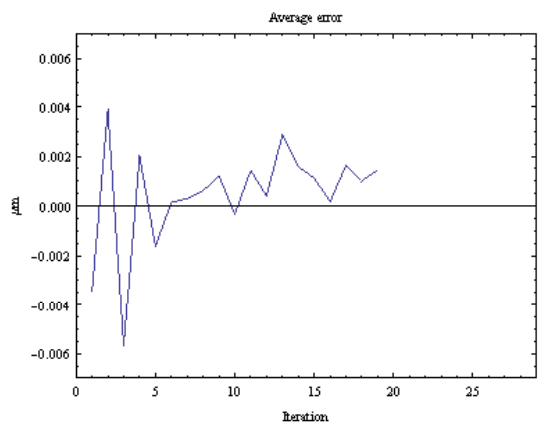

Error distribution, central 24x24 pixels

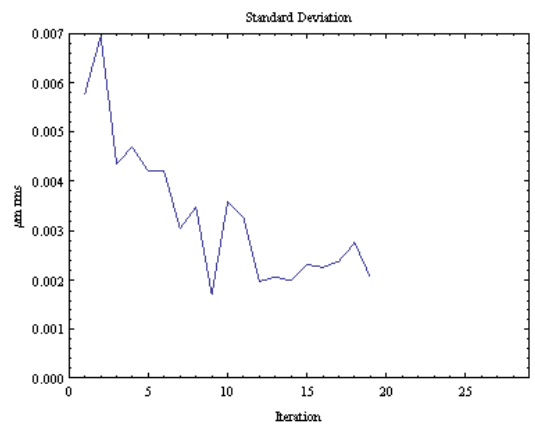

Average error
μm
Iteration

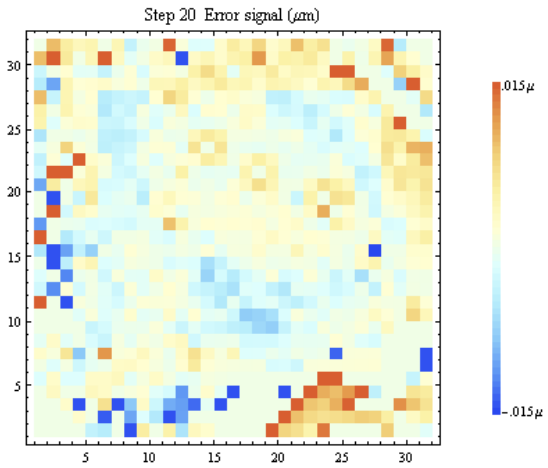

Standard Deviation
μm rms
Iteration

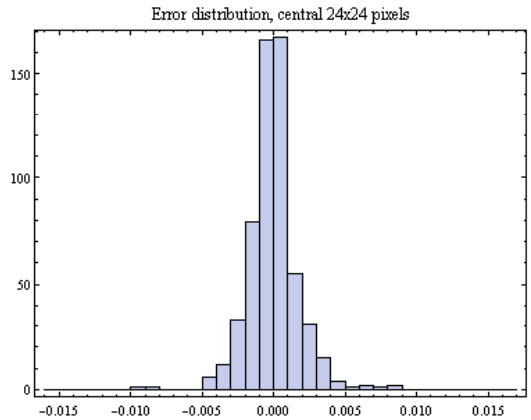

Step 19 Error signal (μm)
.015μ
-.015μ

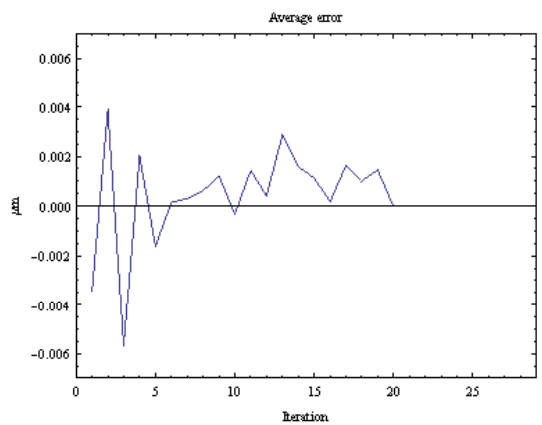

Error distribution, central 24x24 pixels

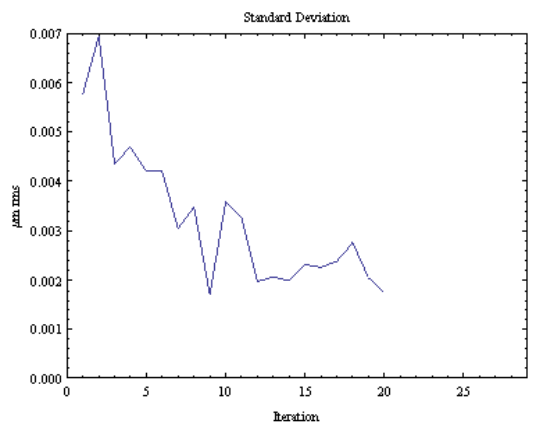

Average error
μm
Iteration

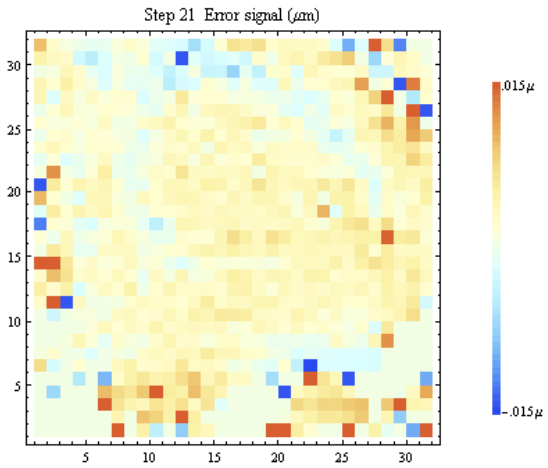

Standard Deviation
μm rms
Iteration

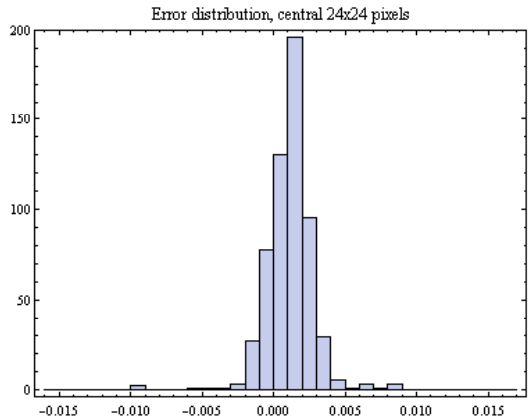

Step 20 Error signal (μm)
.015μ
-.015μ

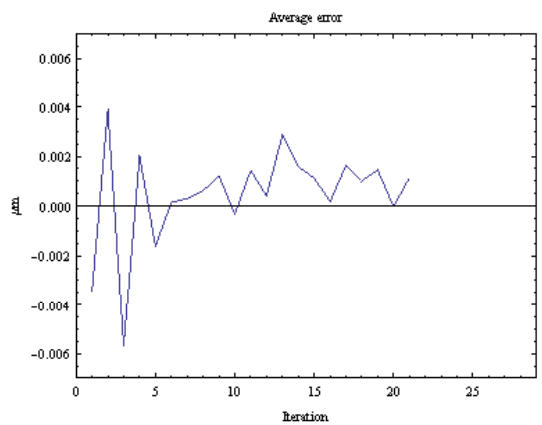

Error distribution, central 24x24 pixels

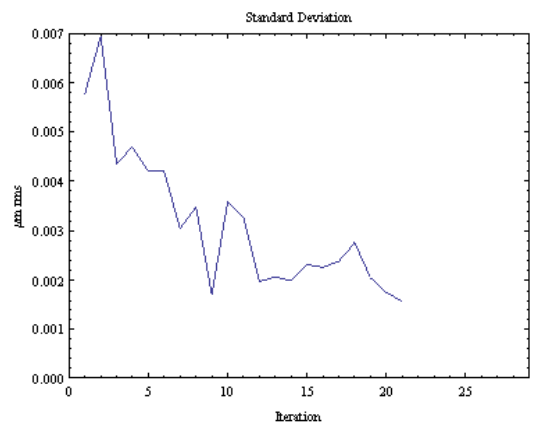

Average error
μm
Iteration

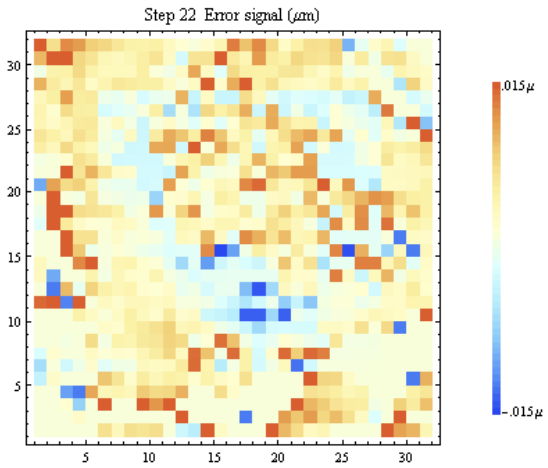

Standard Deviation
μm rms
Iteration

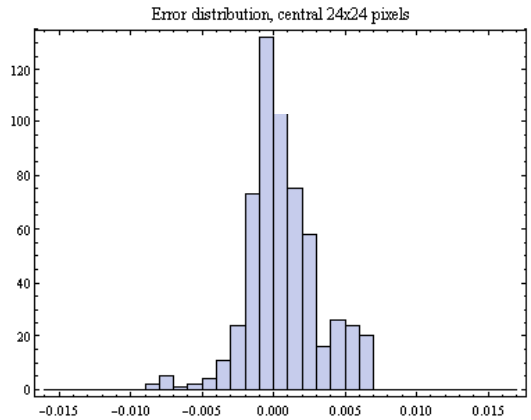

Step 21 Error signal (μm)
.015μ
-.015μ

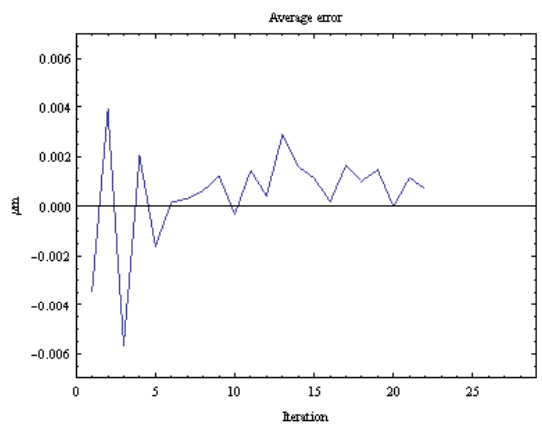

Error distribution, central 24x24 pixels

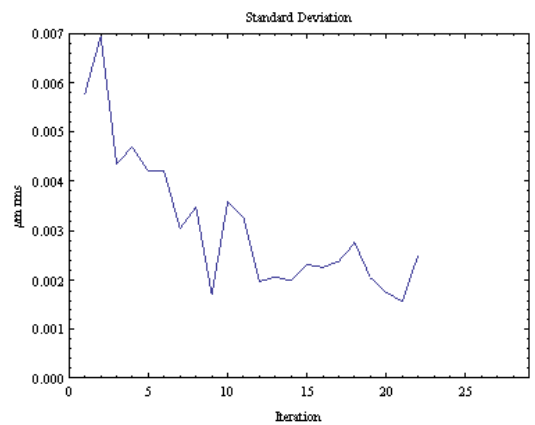

Average error
μm
Iteration

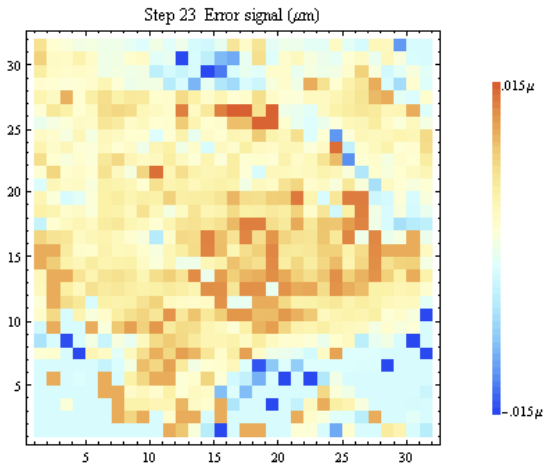

Standard Deviation
μm rms
Iteration

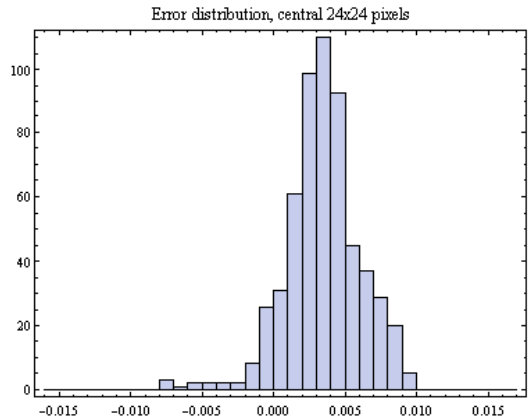

Step 22 Error signal (μm)
.015μ
-.015μ

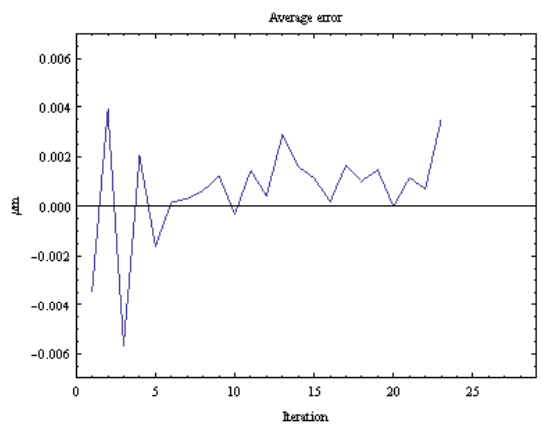

Error distribution, central 24x24 pixels

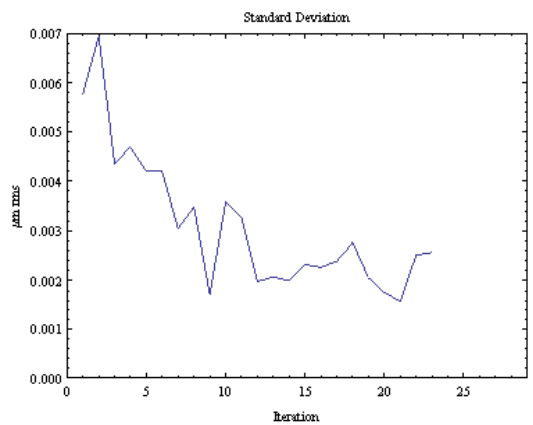

Average error
μm
Iteration

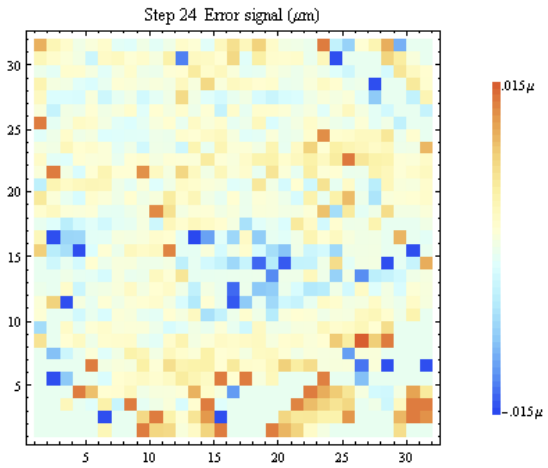

Standard Deviation
μm rms
Iteration

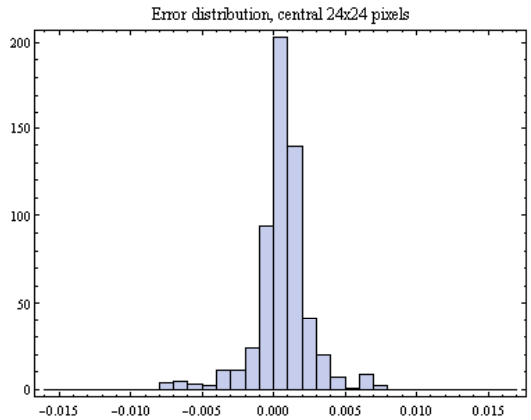

Step 23 Error signal (μm)
.015μ
-.015μ

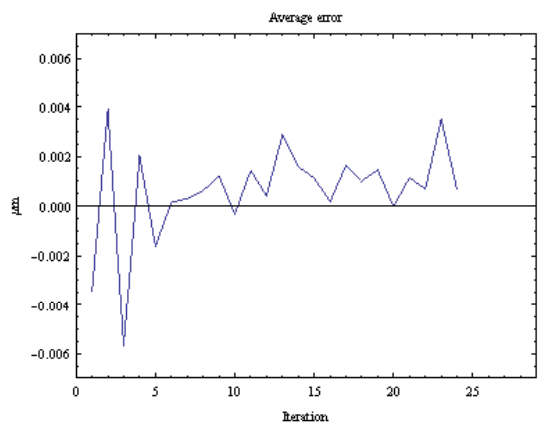

Error distribution, central 24x24 pixels

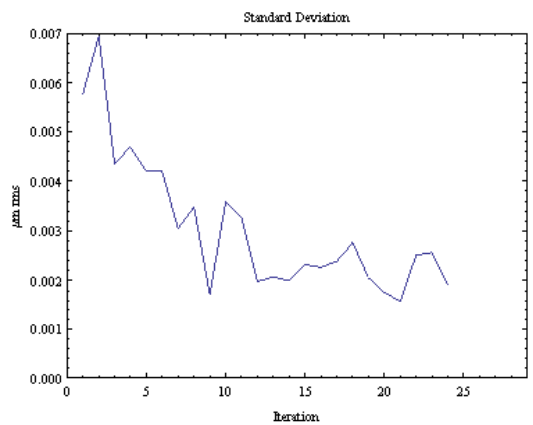

Average error
μm
Iteration

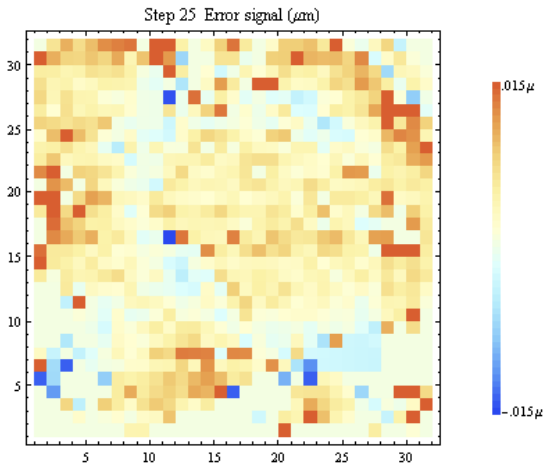

Standard Deviation
μm rms
Iteration

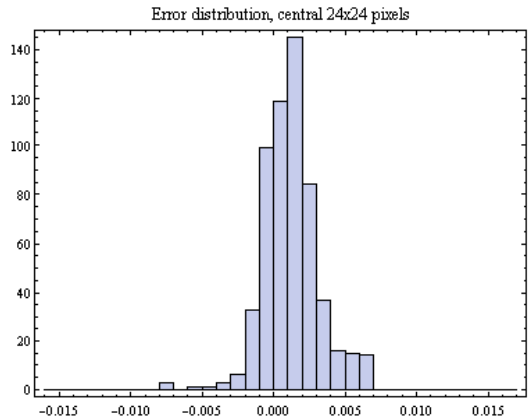

Step 24 Error signal (μm)
.015μ
-.015μ

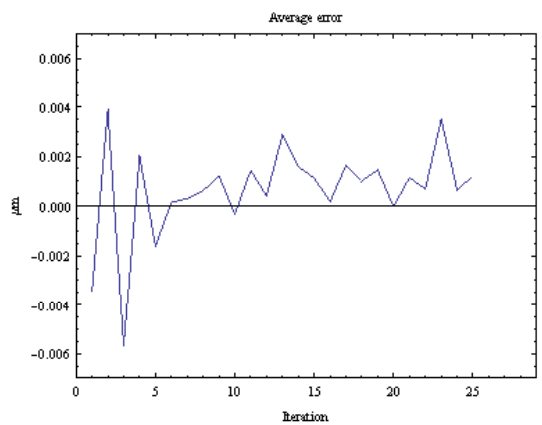

Error distribution, central 24x24 pixels

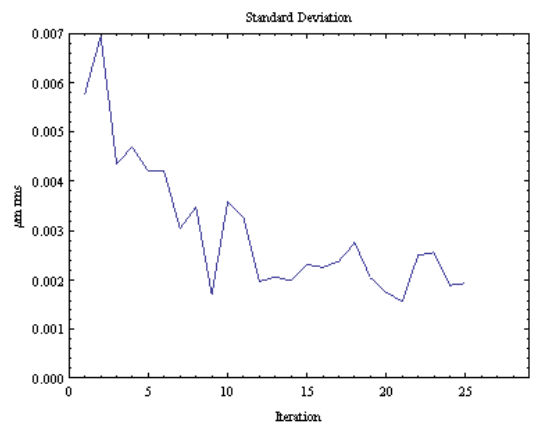

Average error
μm
Iteration

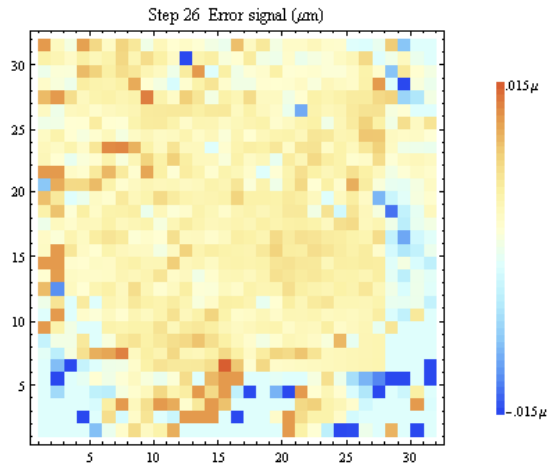

Standard Deviation
μm rms
Iteration

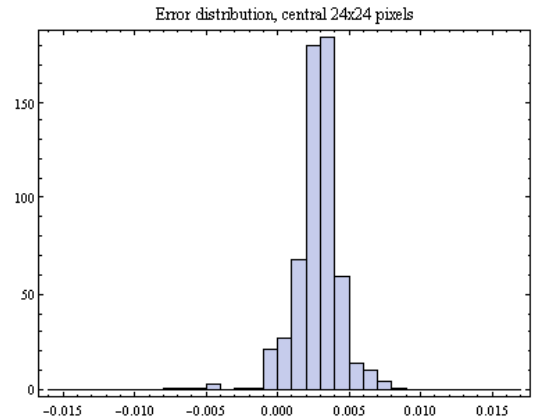

Step 25 Error signal (μm)
.015μ
-.015μ

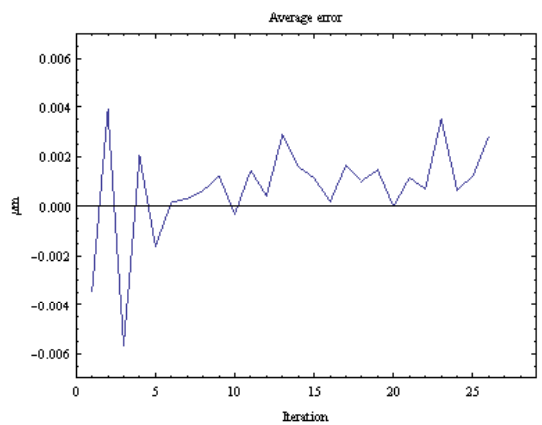

Error distribution, central 24x24 pixels

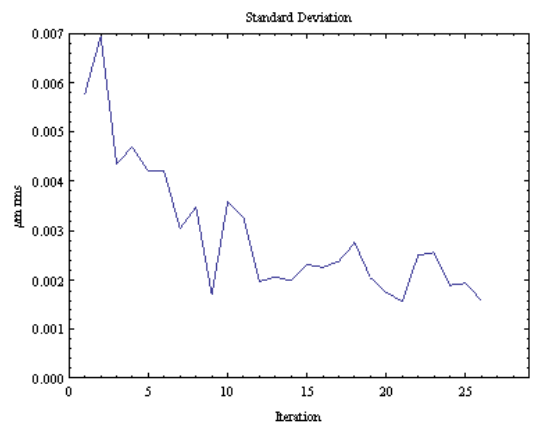

Average error
μm
Iteration

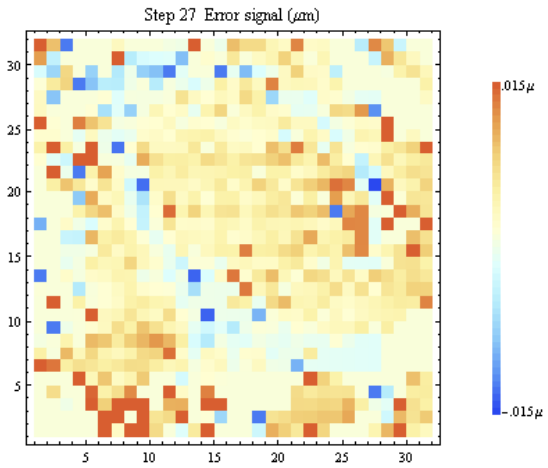

Standard Deviation
μm rms
Iteration

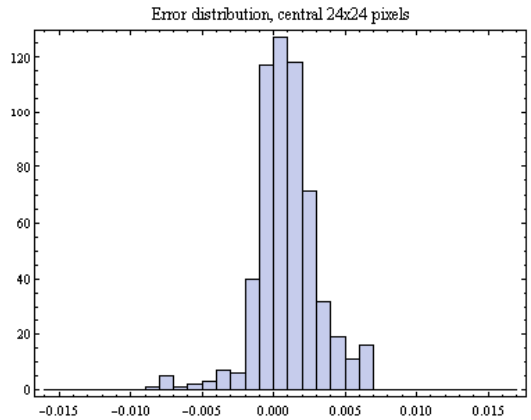

Step 26 Error signal (μm)
.015μ
-.015μ

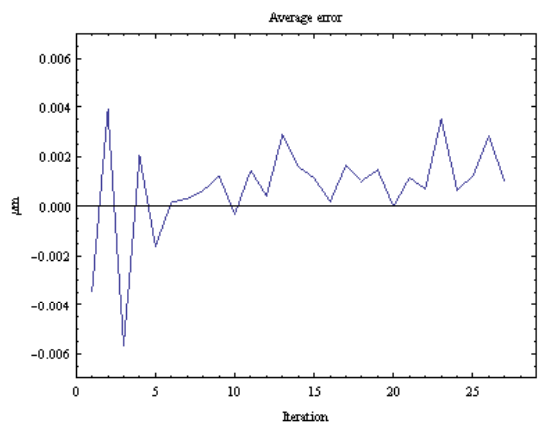

Error distribution, central 24x24 pixels

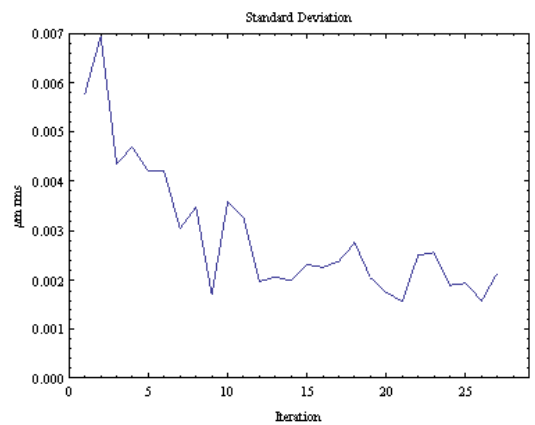

Average error
μm
Iteration

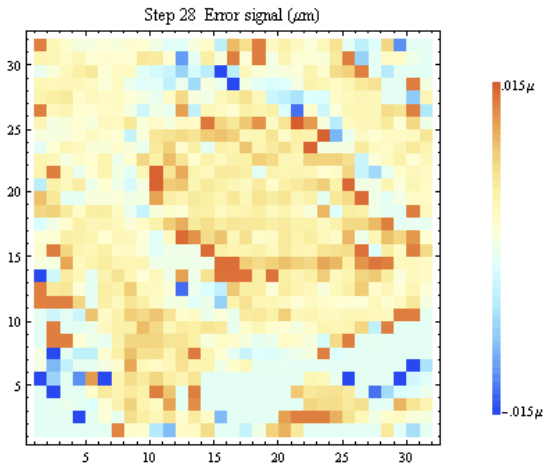

Standard Deviation
μm rms
Iteration

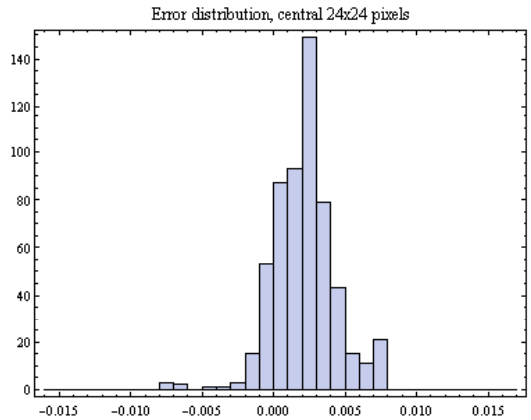

Step 27 Error signal (μm)
.015μ
-.015μ

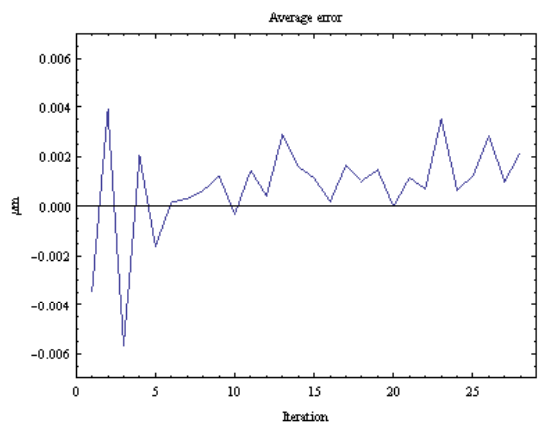

Error distribution, central 24x24 pixels

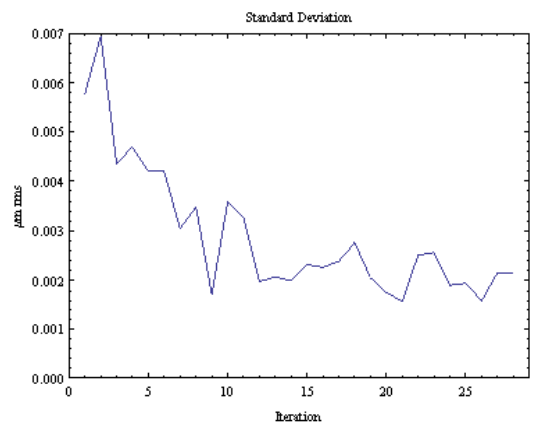

Average error
μm
Iteration

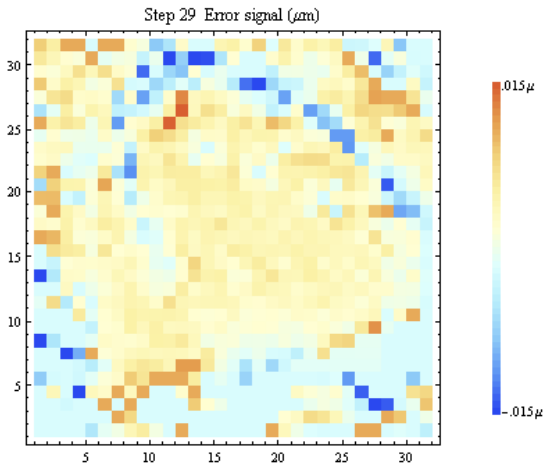

Standard Deviation
μm rms
Iteration

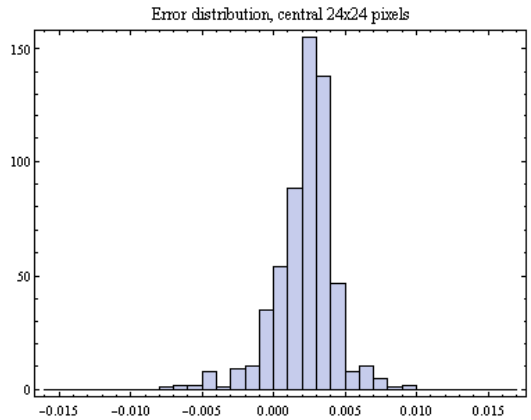

Step 28 Error signal (μm)
.015μ
-.015μ

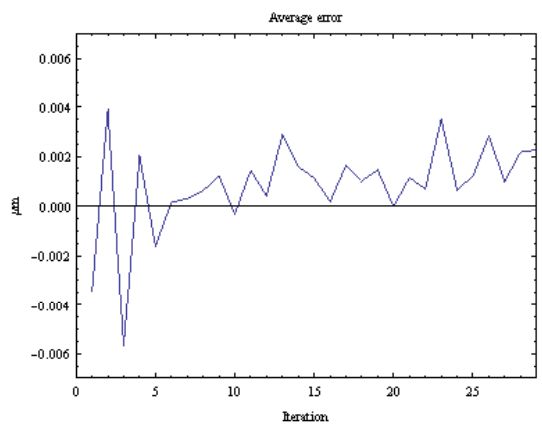

Error distribution, central 24x24 pixels

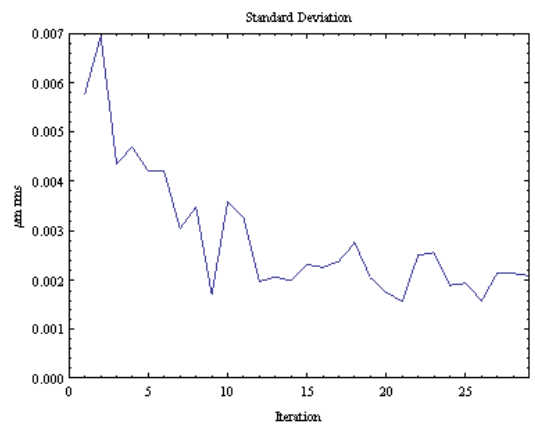

Average error
μm
Iteration


Standard Deviation
μm rms
Iteration


Step 29 Error signal (μm)
.015μ
-.015μ


Error distribution, central 24x24 pixels


Average error
μm
Iteration

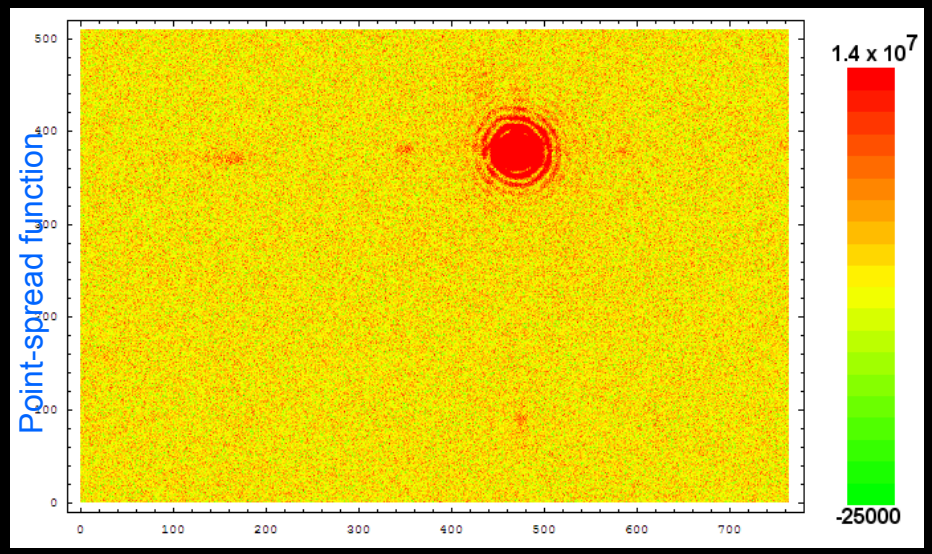

Standard Deviation
μm rms
Iteration

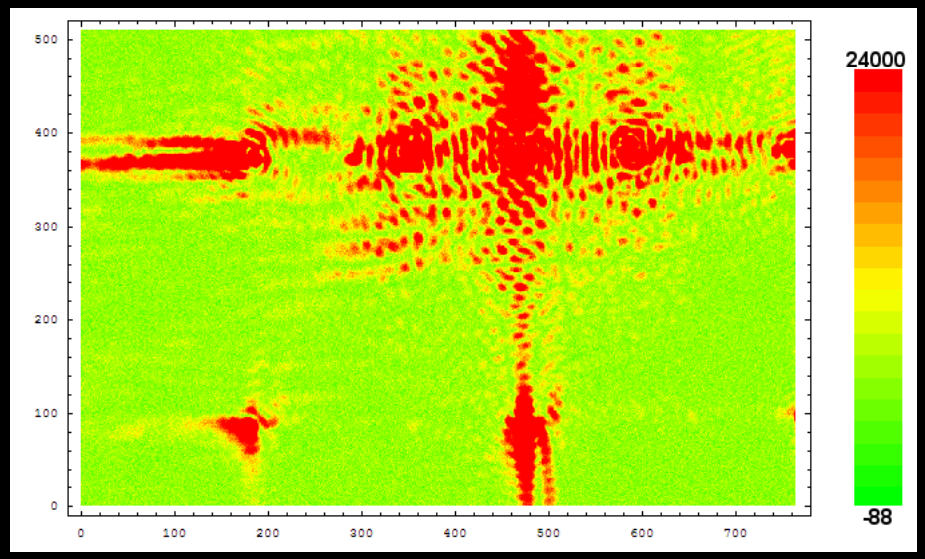
Starlight suppression

Constructive interference

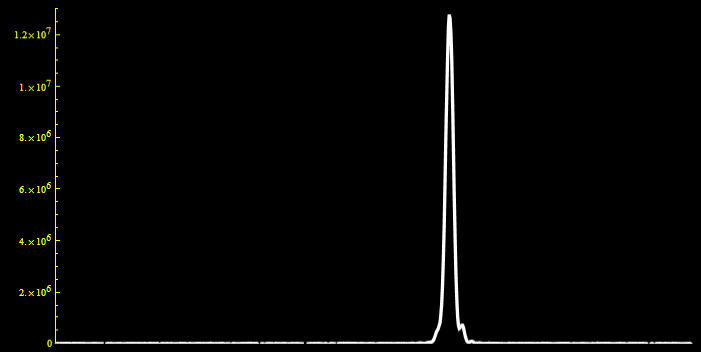
Destructive interference

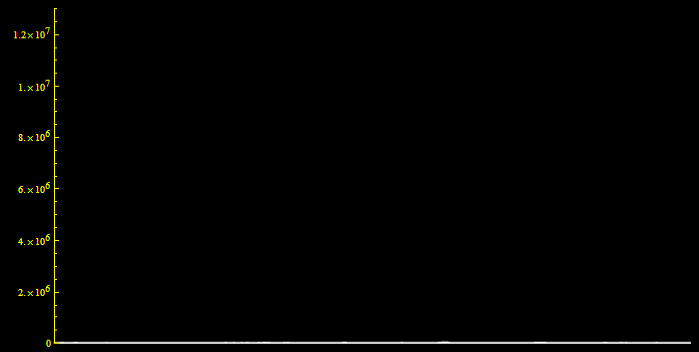
Point-spread function





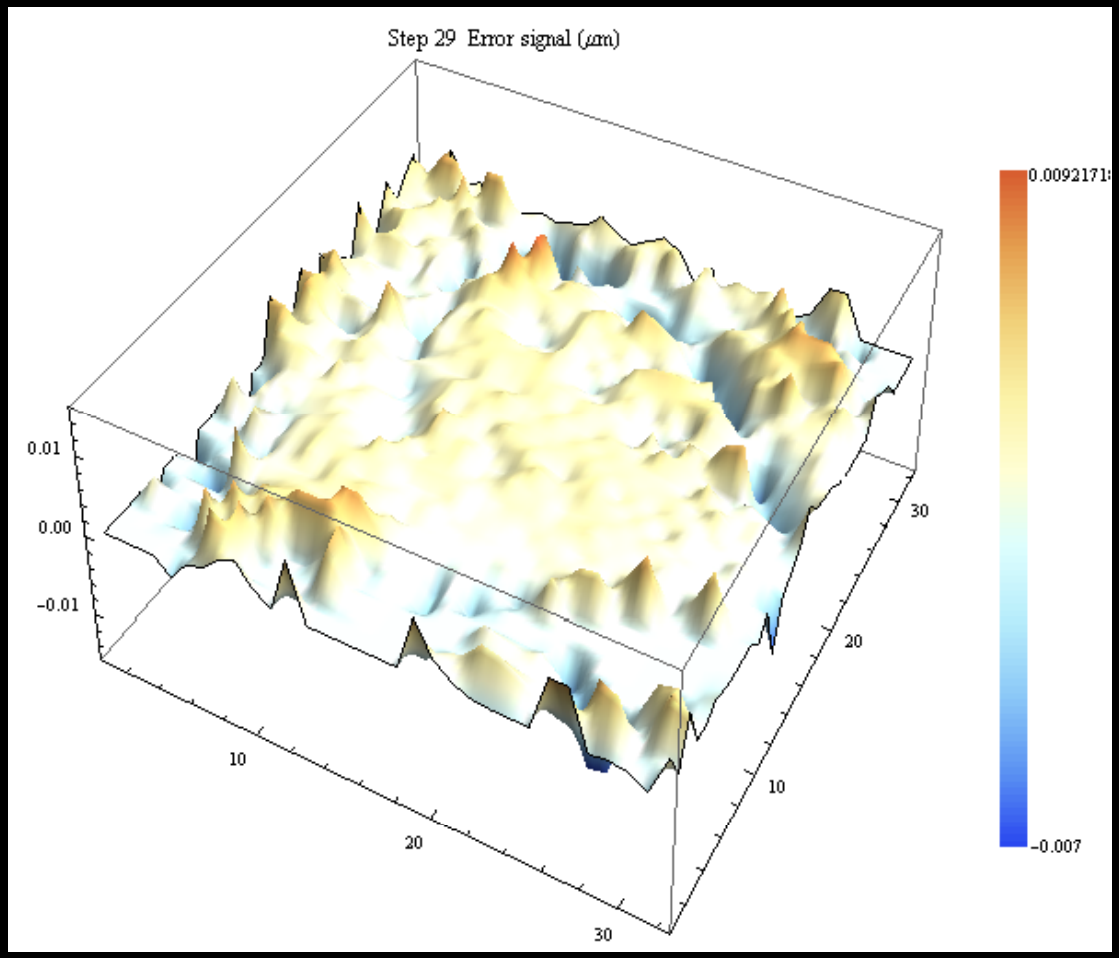
Cross section





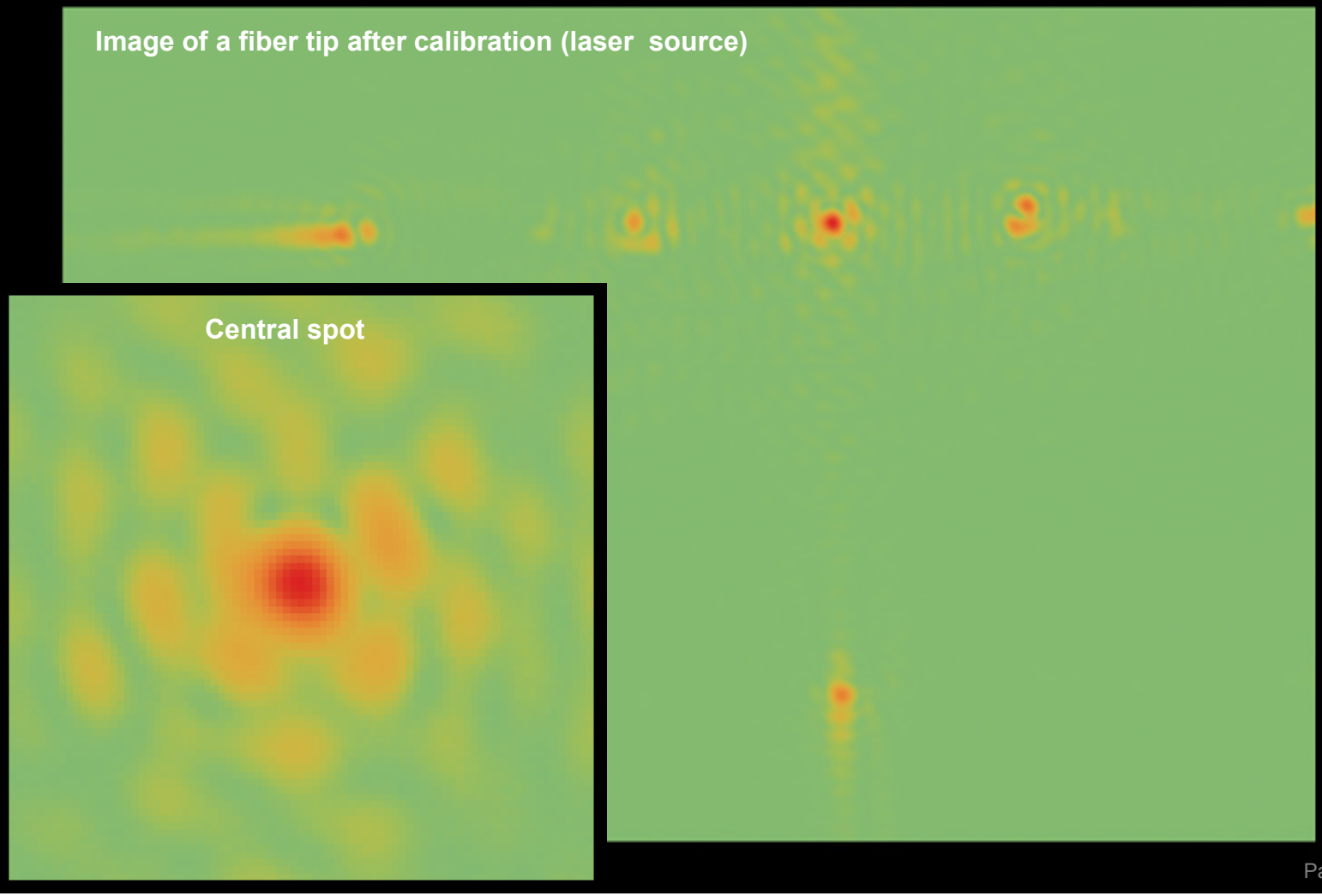
Results

- Calibration reduces path error to ~few nm



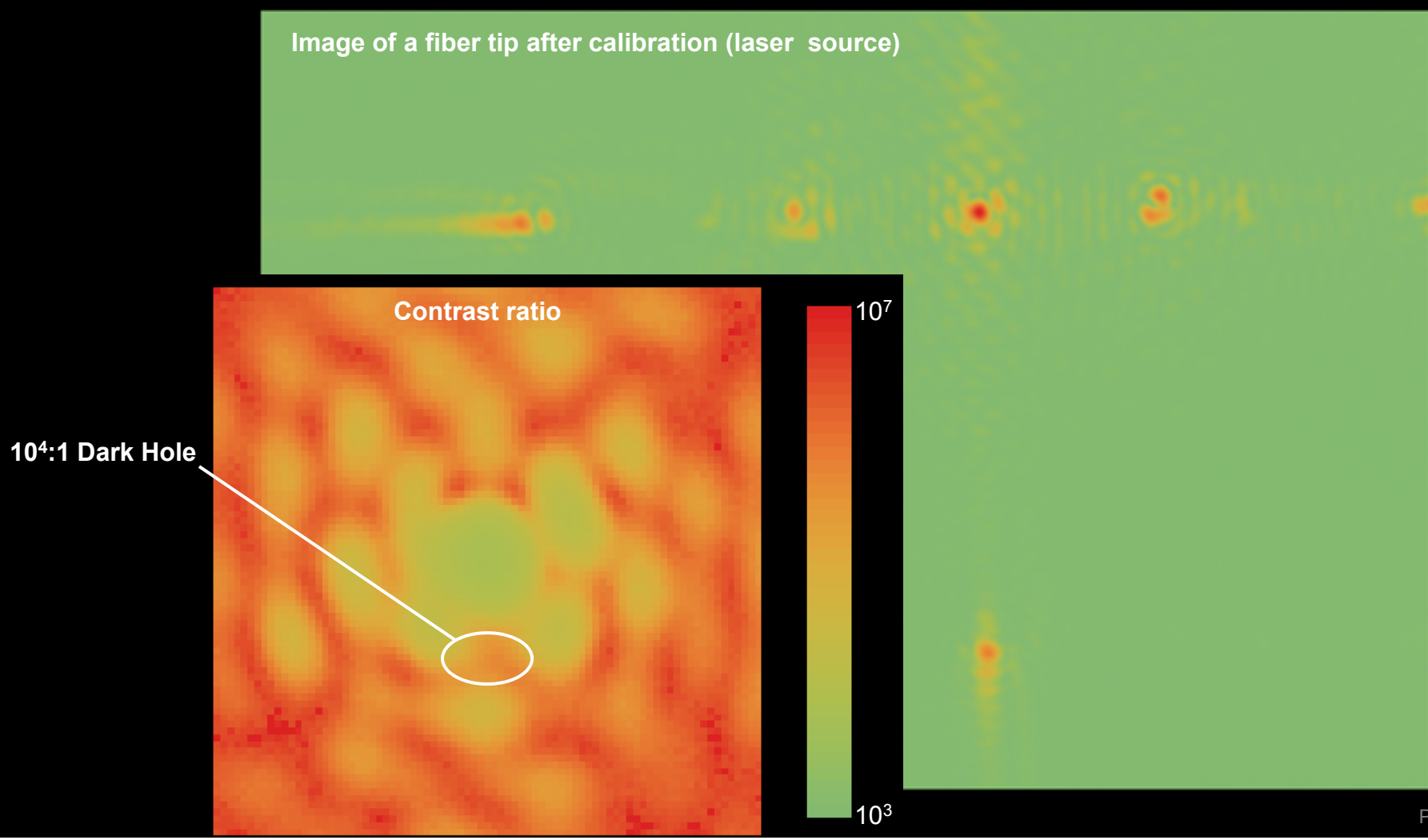
Results

- Center suppressed 600:1 in laser light
- Residual speckle pattern needs some work



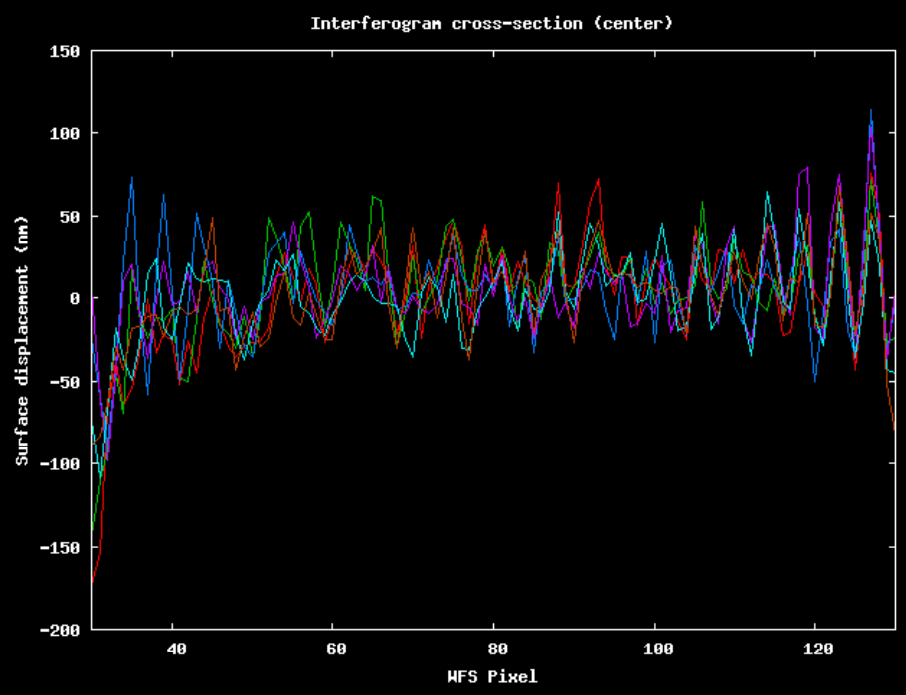
Results

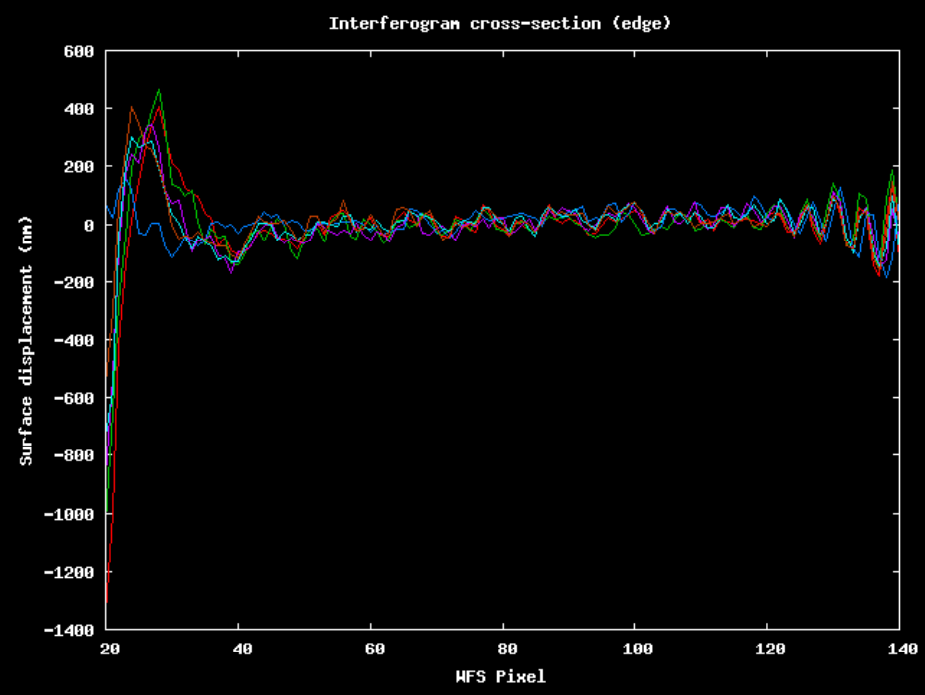
- Center-to-speckle contrast ratio > 10,000 at 1st Airy Ring



What's next

- Improve acoustic noise
- Faster processing
- Image processing, half-plane dark hole, etc.
- Improve DM surface finish





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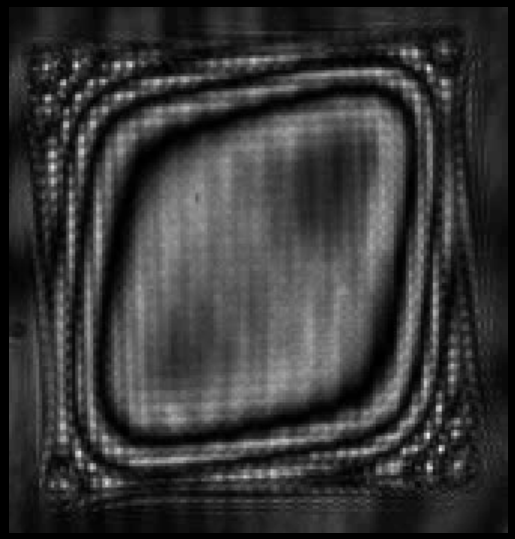
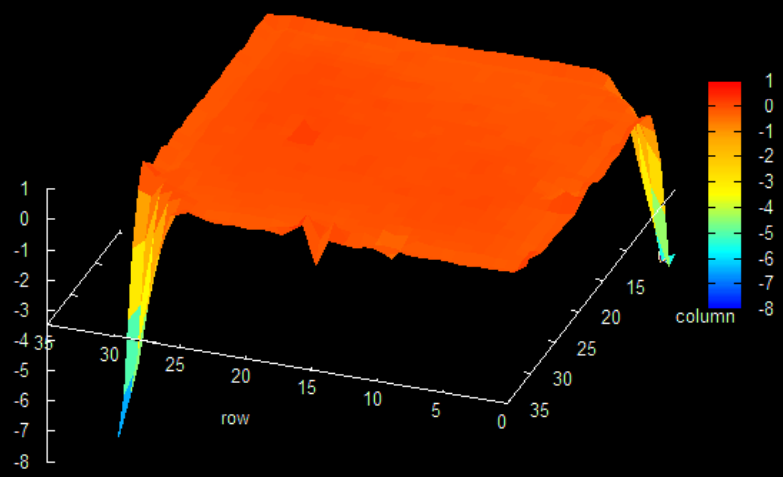


Nuller pupil



Unwrapped phase (radians)

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