TMT
THIRTY METER TELESCOPE

Phasing of Large Optical Segmented Ground-Based Telescopes

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Definition of Phasing

- Phasing is the adjustment of segments in piston degree of freedom only
- After segment re-installation at Keck the following alignments are routinely performed with a Shack-Hartman camera:
  - Segment ID
  - Coarse segment tip/tilt
  - Secondary mirror rigid body
  - Measurement of segment figures
  - Phasing of segments: adjustment of piston degree of freedom only
- This talk will concentrate on the most difficult of the above items: Phasing

Outline

- Review of current telescopes and techniques
- Basic description of “Shack-Hartmann” phasing
- Narrow band phasing – capture range +/- $\lambda/4$
  - How it works
  - On-sky Keck results
  - Testbed results
- Coherence phasing – capture range >> +/- $\lambda/4$
  - How it works
  - On-sky Keck results

Ground-Based Optical Segmented Telescopes-Phasing Techniques

- Keck : “Shack-Hartmann” Phasing (used >1000 times)
  - Phase Discontinuity Sensing as an “optional” method
- GTC: “Shack-Hartmann” Phasing
- ESO Alignment and Phasing Experiment
  - SHAPS: “Shack-Hartmann” Phasing
  - ZEUS: “Zernike Unit for Segment Phasing”
  - PYPS: “Pyramid Phase Sensor”
  - DIPSI: “Diffraction Image Phase Sensing Instrument”
- Planned telescopes
  - Thirty Meter Telescope (TMT): “Shack-Hartmann” Phasing
  - European-ELT: “Shack-Hartmann” Phasing

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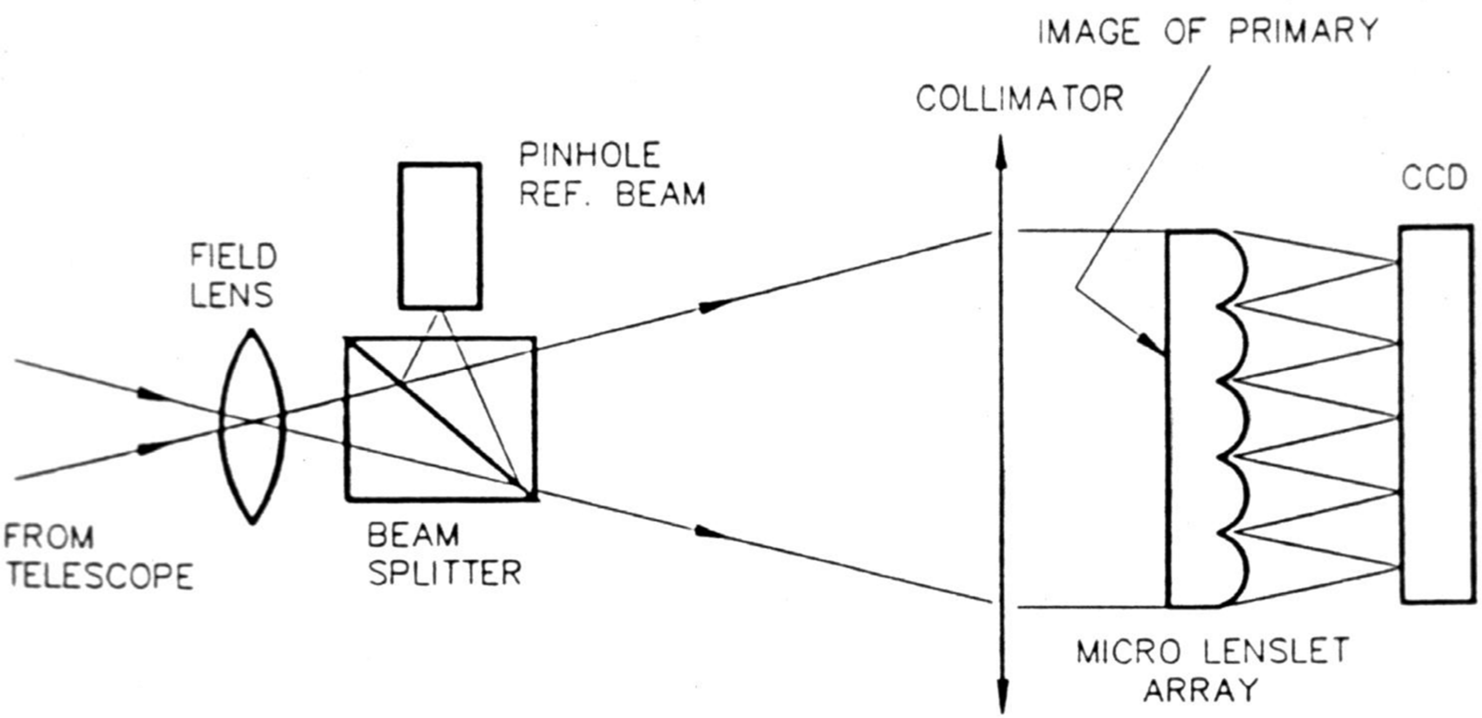
Shack Hartmann Test



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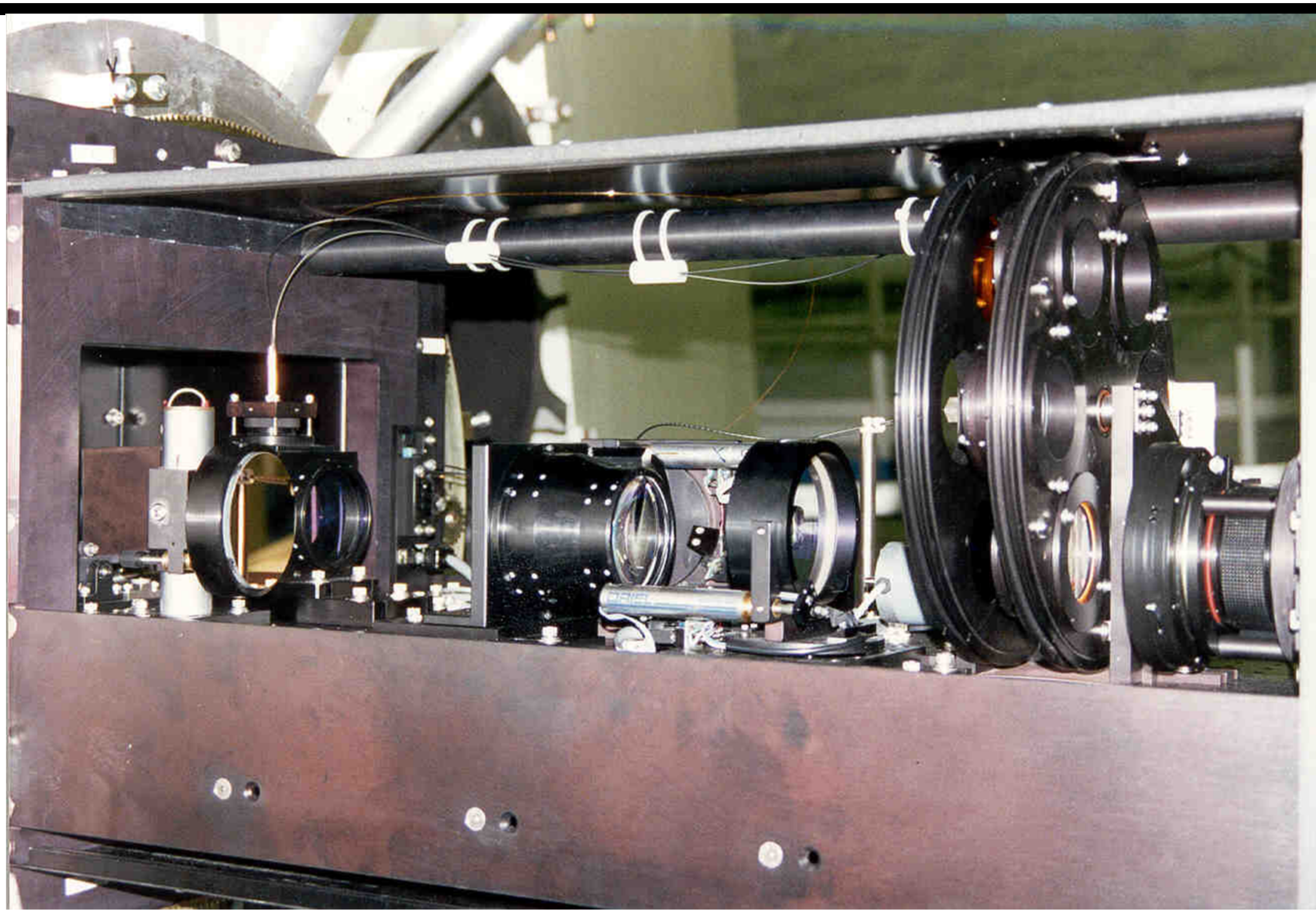
Keck Phasing (and Alignment) Camera



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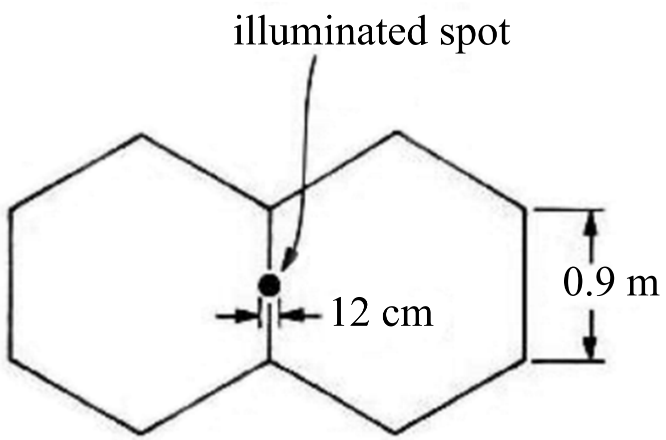
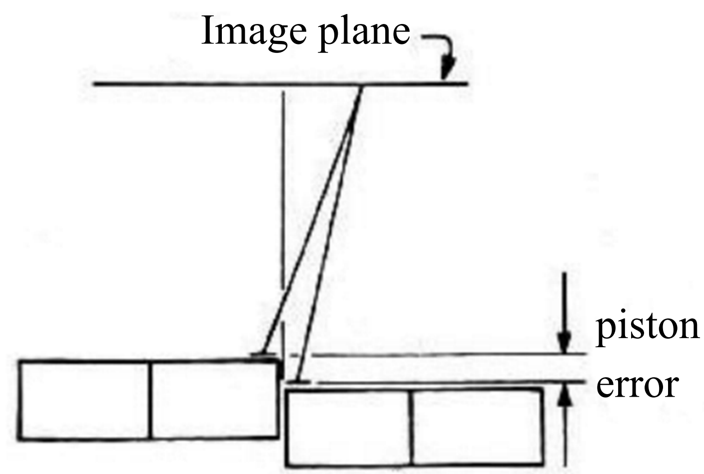
Segment Phasing

Top View

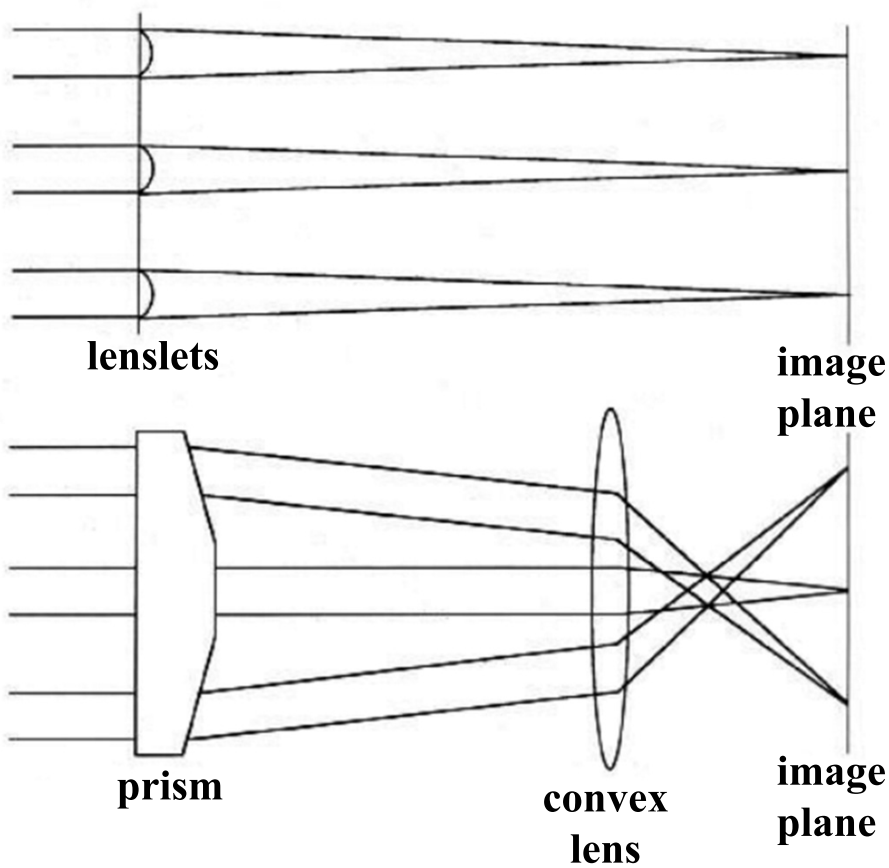


Side View



- Phasing subaperture size selected to be smaller then r_0.

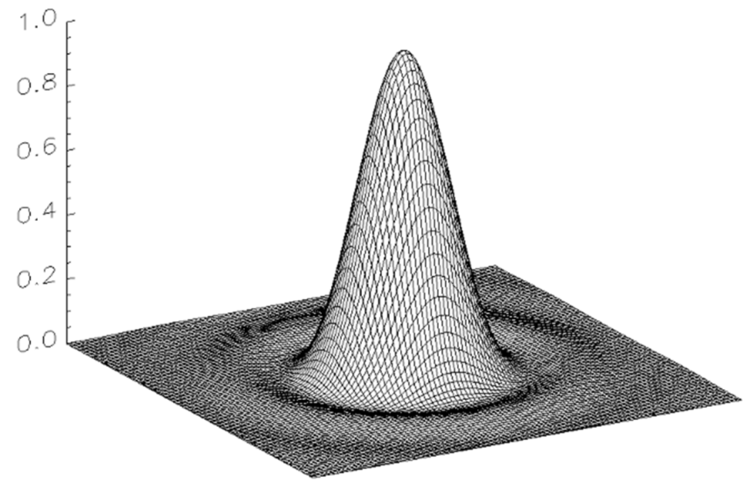
Multiple Choices for Forming Sub-Images Lenslets, Prisms, Masks



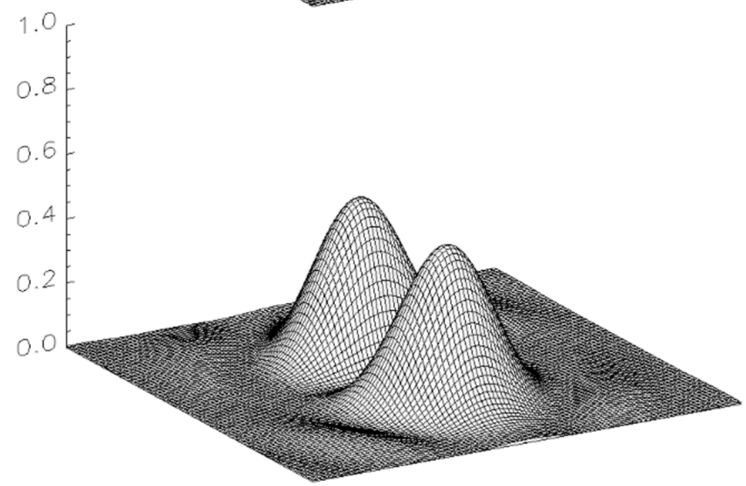
- Lenslets
  - Need to worry about quality
  - Commercially available
  - Expensive
- Prisms
  - Good image quality
  - Hard to make large arrays
- Masks (Fresnel diffraction)
  - Good image quality
  - Inexpensive
  - System parameters define if this approach will work

In and Out of Phase Subimages

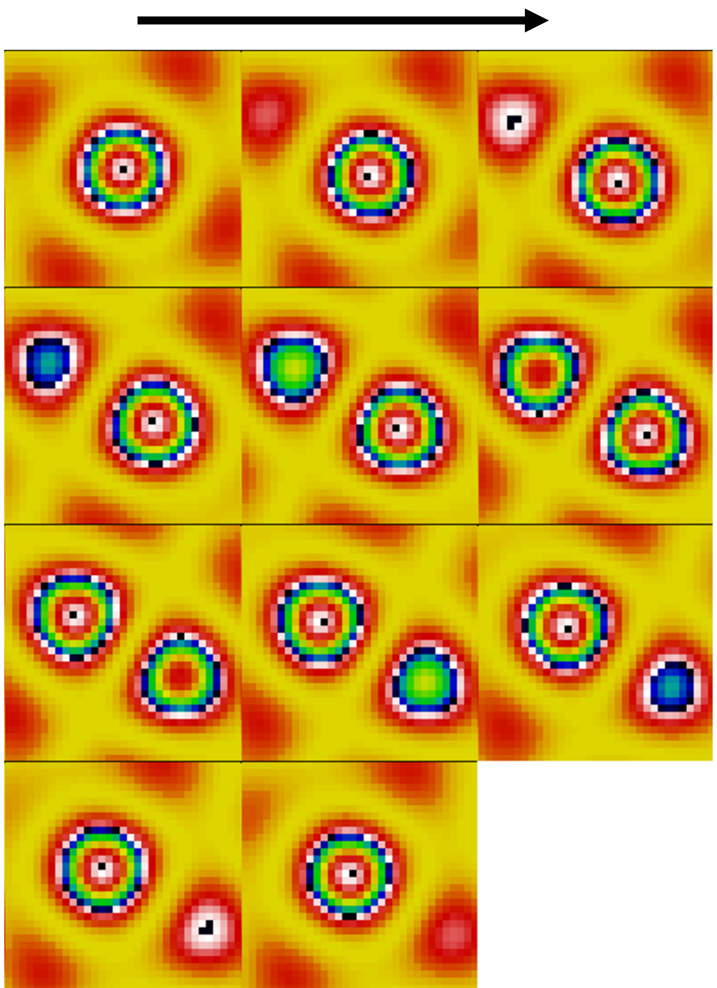
$$\text{Piston Error} = 0$$

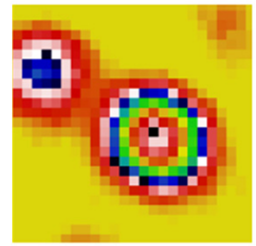


$$\text{Piston Error} = \frac{\lambda}{4}$$



Phasing Template Sequence
(891 nm filter, 10 nm FWHM)





$$\text{Step Size} = \frac{\lambda}{22} = 40 \text{ nm}$$

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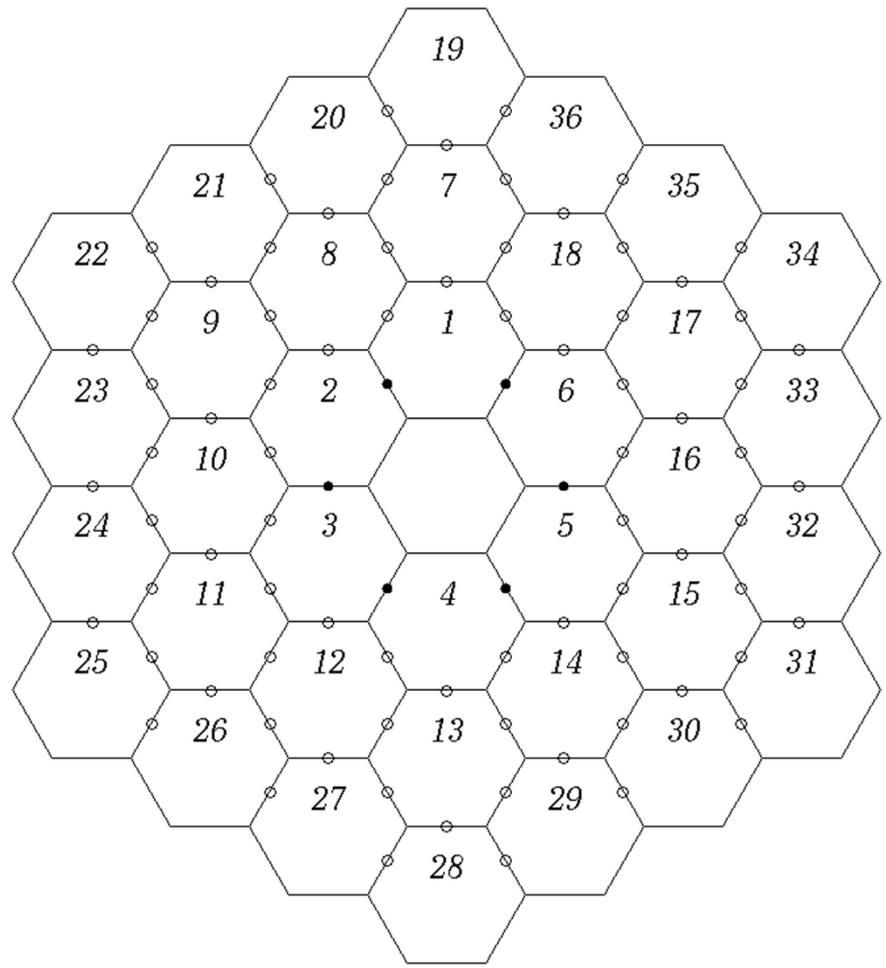
Phasing Keck Telescope

- 78 edge-sampled spots used in phasing
- 120 mm diameter



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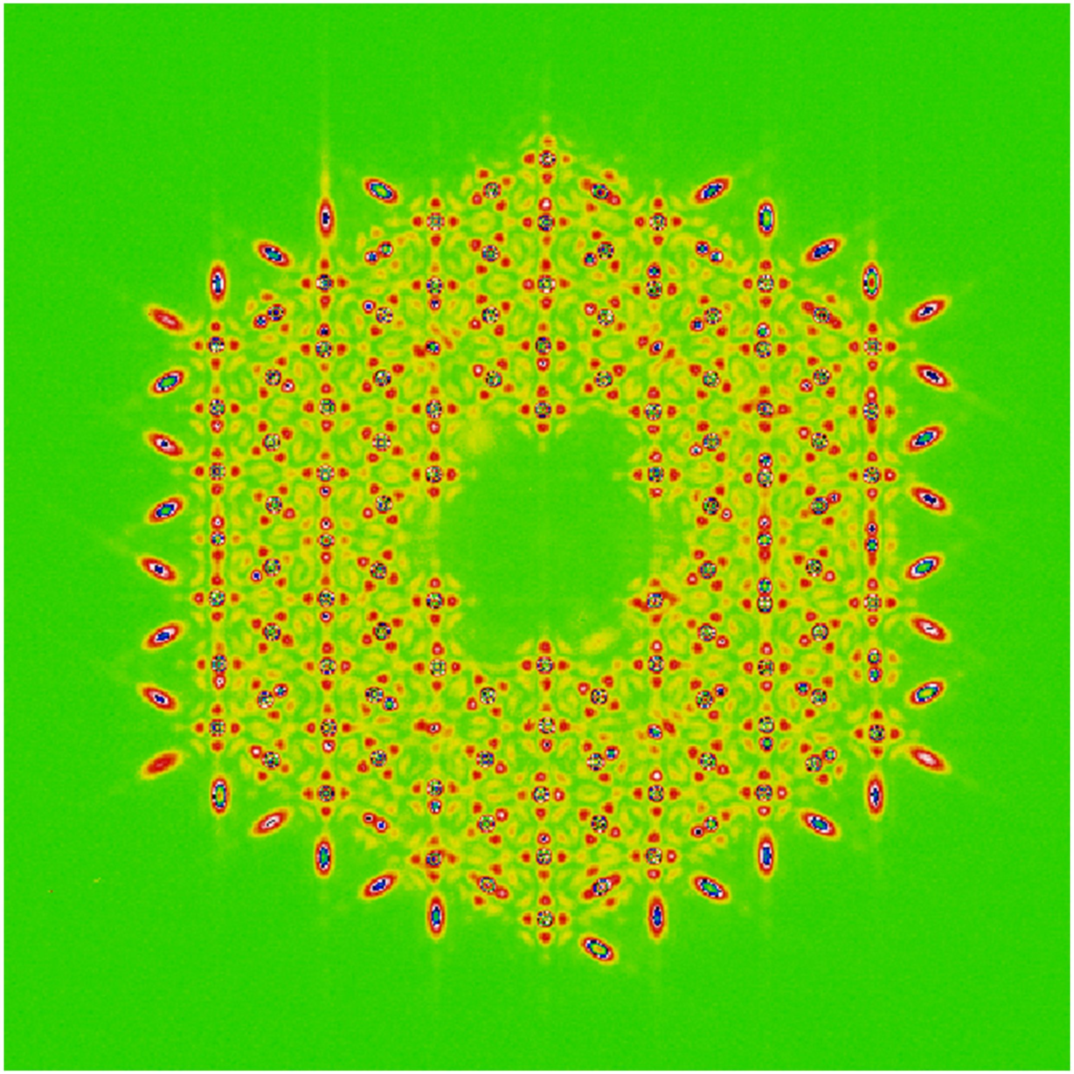
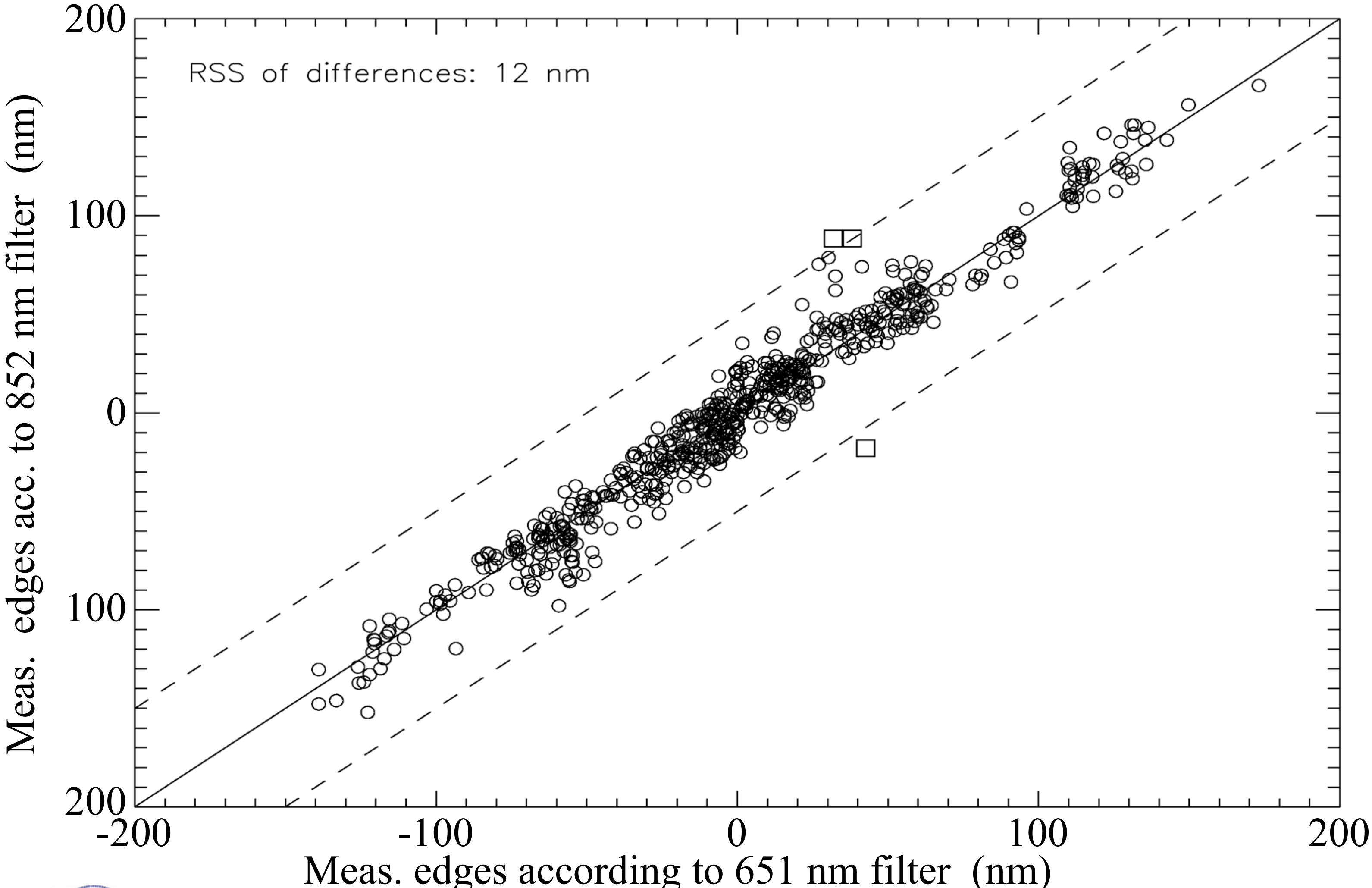
Narrowband Phasing – Keck Data (852 nm filter)



Phasing: 852 nm vs 651 nm



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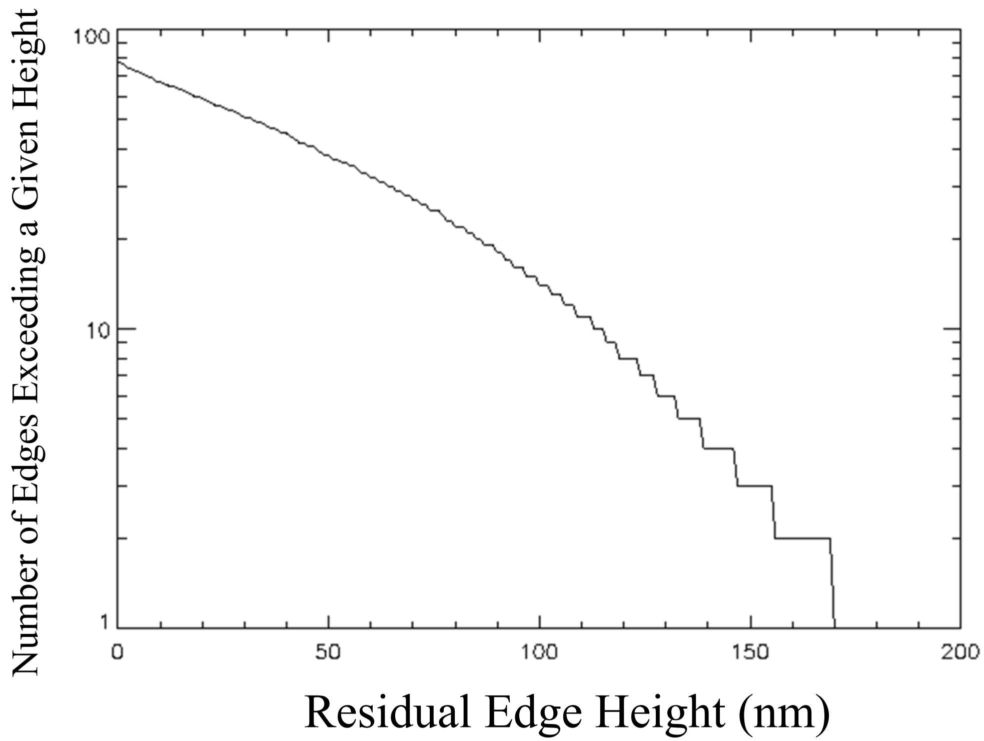
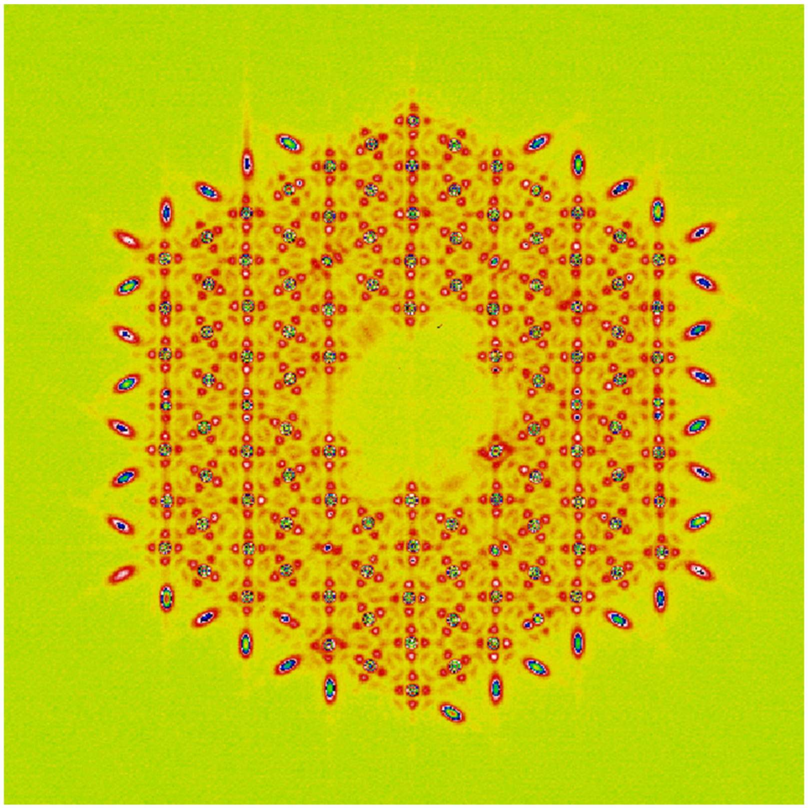
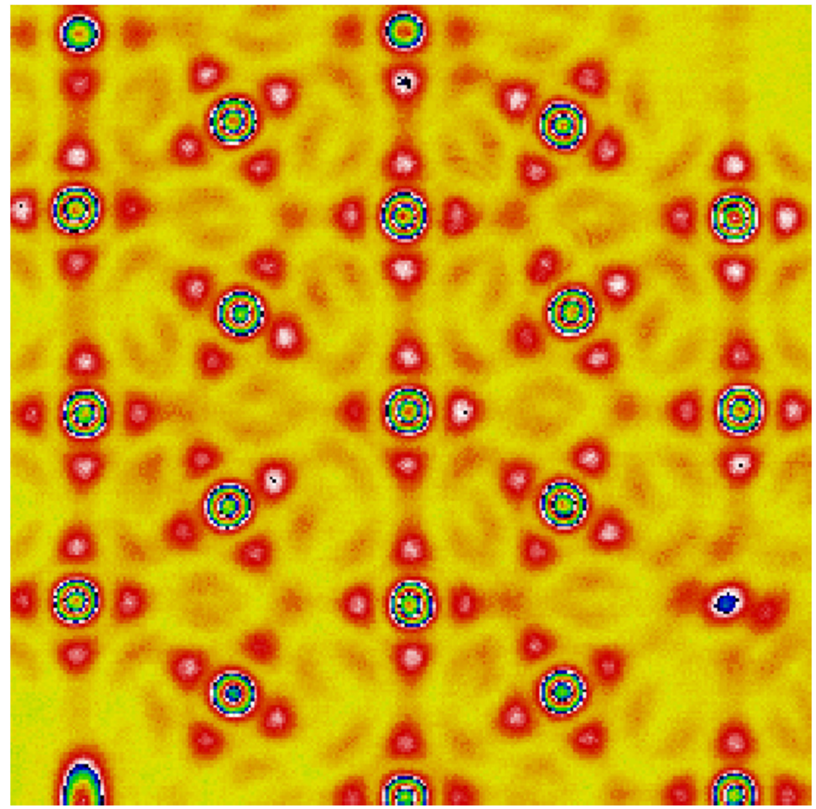
Narrowband Phasing Limitation

- When edge step approaches λ/4 (220 nm), measurement becomes uncertain by λ/2
- "Effective" capture range reduced to: 220 nm – max edge residual



Phasing with Perfect Segments (use Segment Tip/Tilt to align edges)



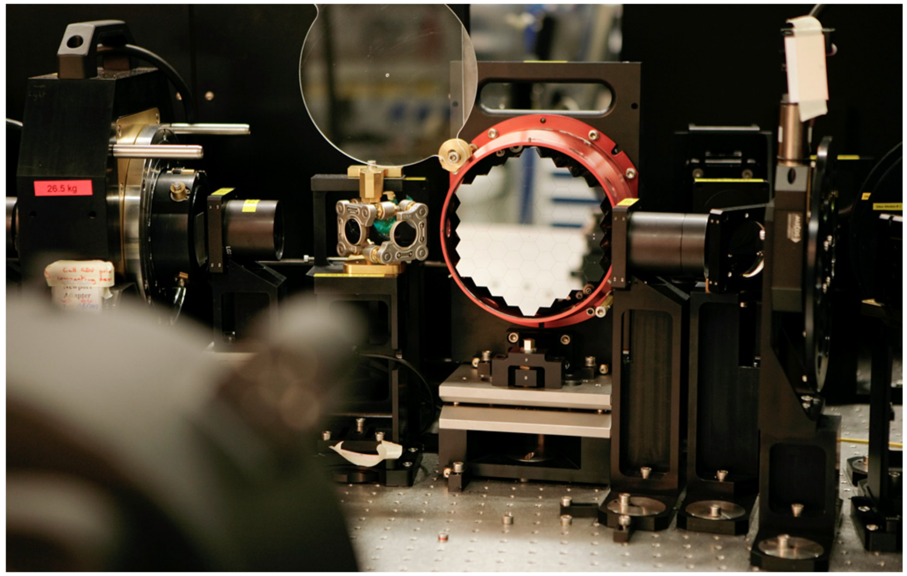


- Piston RMS = 2 nm
- RMS edge residual = 9 nm

Fresnel Phasing

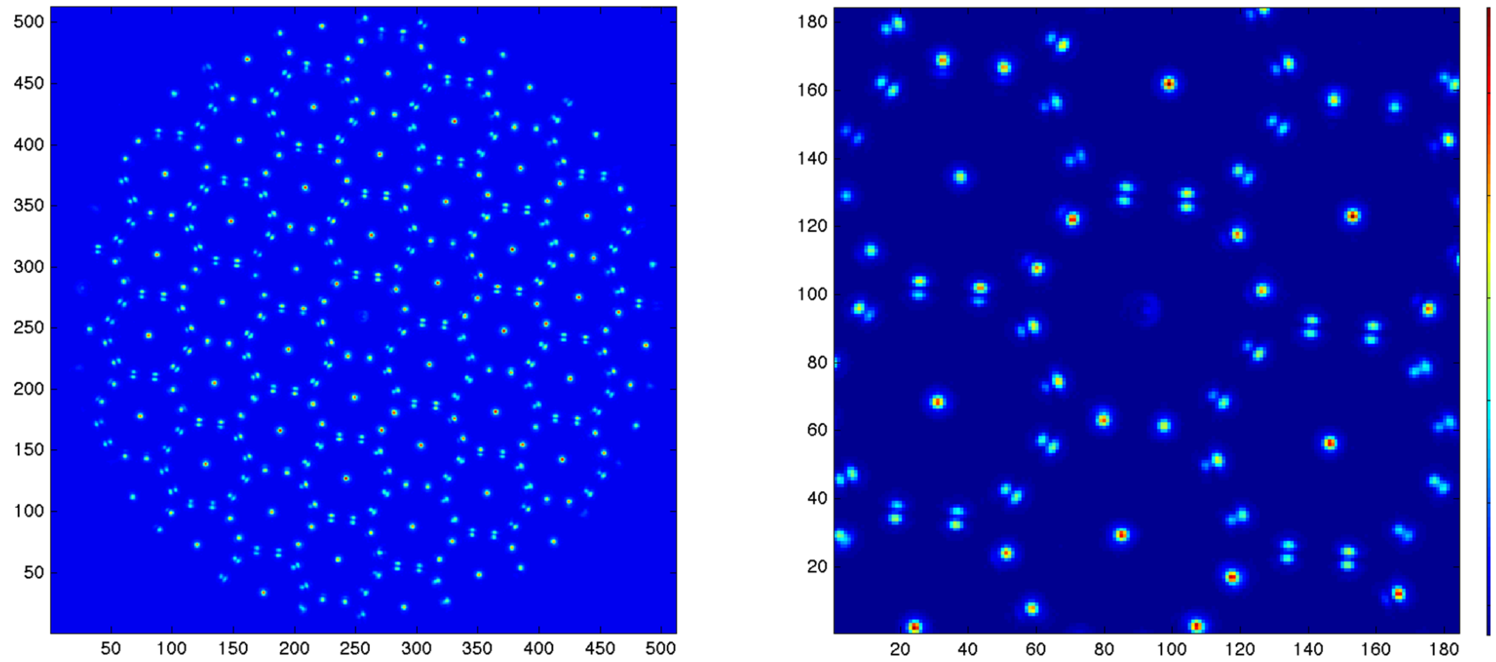
- Fresnel number of a lens: $F = a^2/f\lambda$
  - a = radius of lens
  - f = focal length of lens
  - λ = wavelength of observation
- For F < 1, Fresnel and Fraunhofer diffraction patterns are very similar.
- This means that to a first approximation one can replace the lenslet array with a mask consisting of clear apertures.
- For the nominal design of the TMT Alignment and Phasing System, the Fresnel number of the lenslets is F = 0.6. [The Keck system has F = 1.3.]

ESO Alignment and Phase Experiment



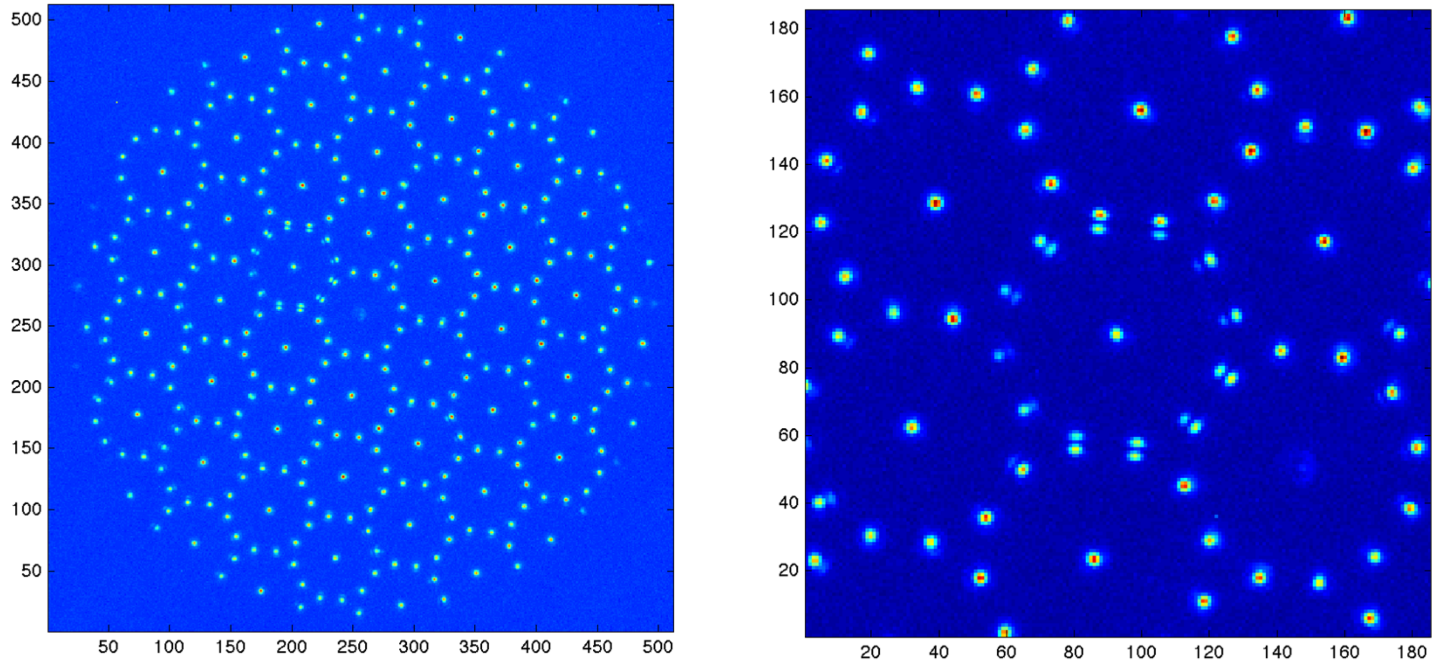
- The ESO Active Phasing Experiment (APE), originally conducted at the VLT, has been set up in the ESO optical labs.
- APE, with its 61 segment actively controlled mirror, provides an ideal testbed for Fresnel phasing.
- We conducted a series of experiments at ESO using APE to confirm Fresnel phasing (with generous support from ESO).

Sample Phasing Image I



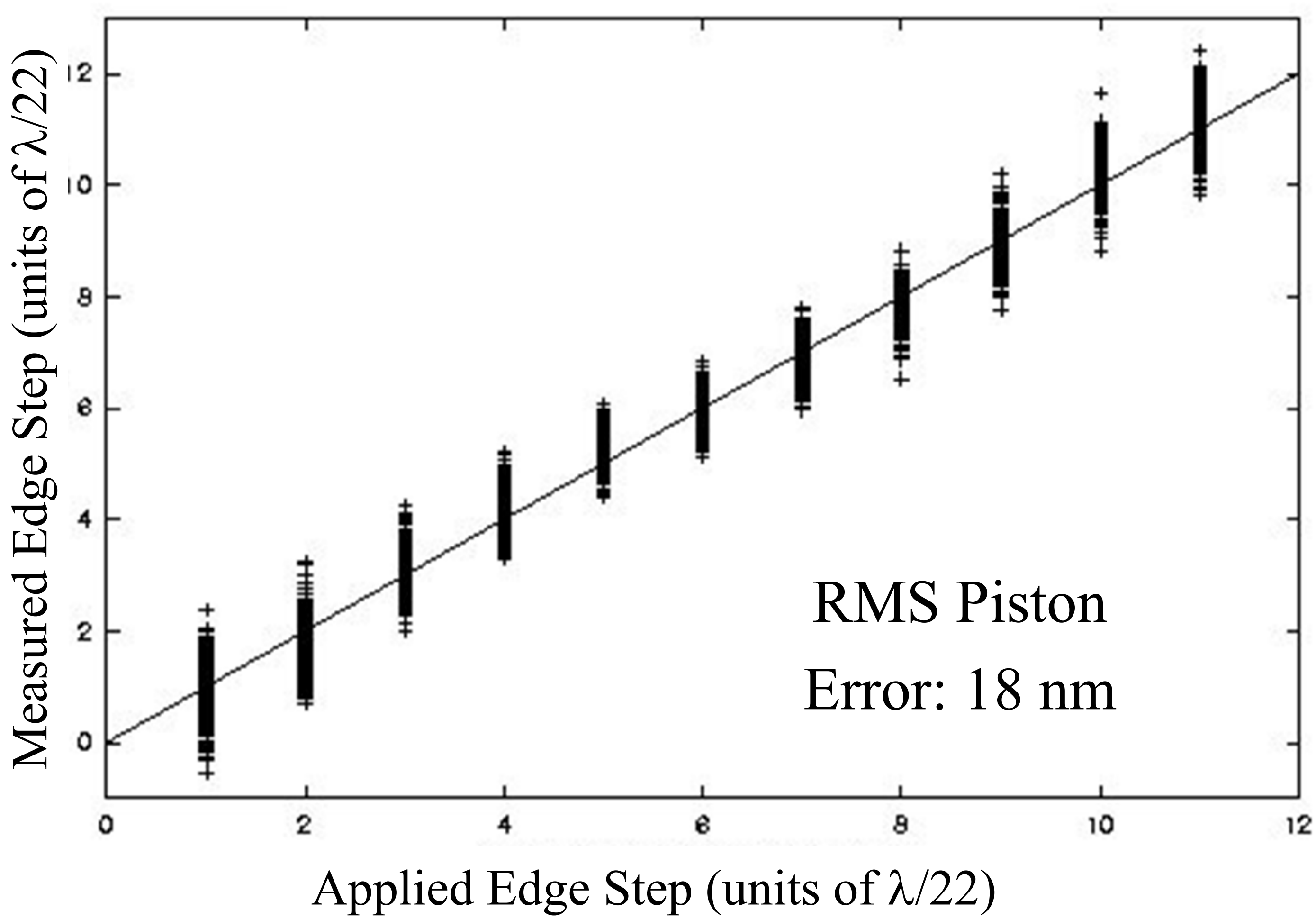
- APE phasing image: all edge steps have 0 (circular subimages) or $\lambda/4$ (split subimages) phase errors.

Sample Phasing Image II

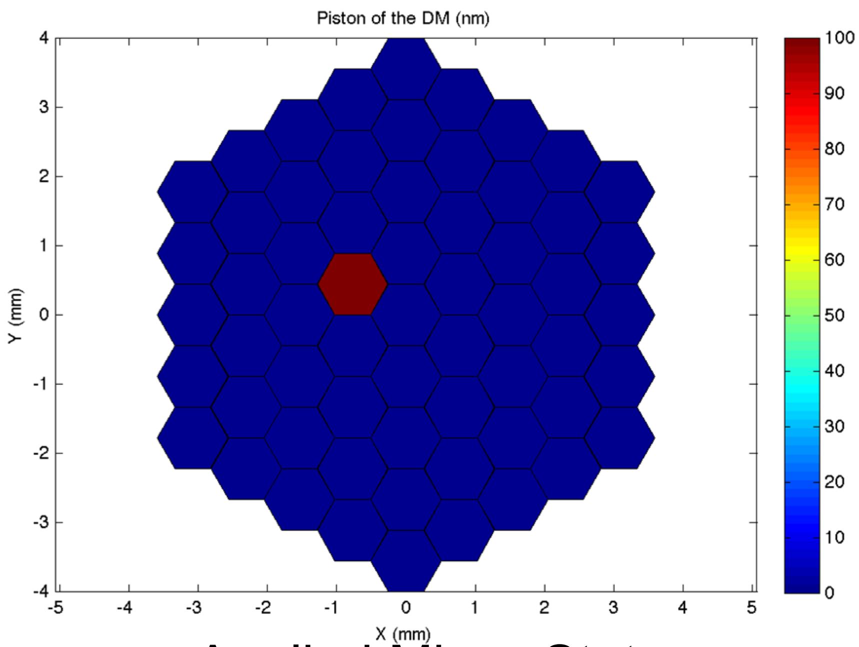


- APE phasing image: one segment pistoned by 100 nm.

Measured vs. Theoretical Edge Steps – Fresnel Phasing

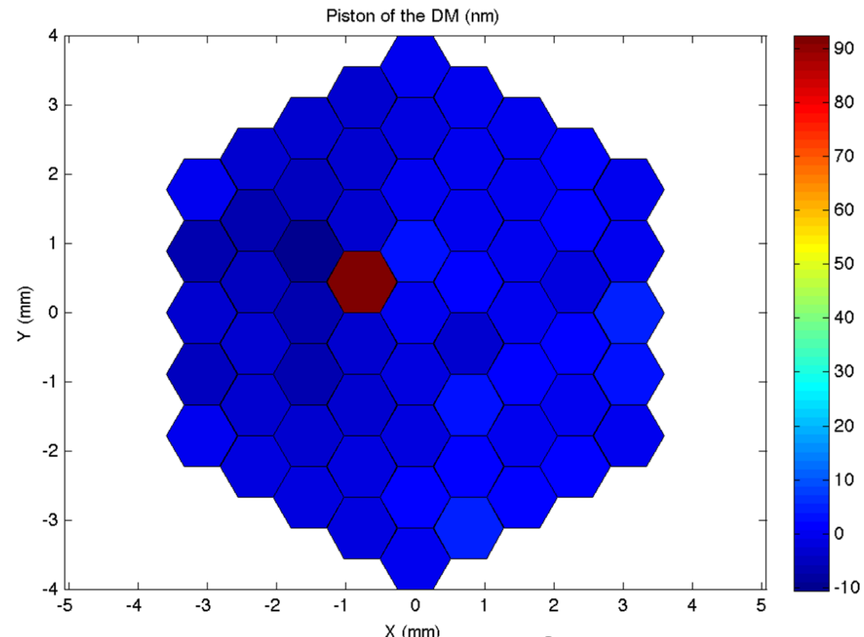


Measuring Piston Error of a Single Segment



Applied Mirror State

(Segment Piston = 100 nm)



Measured Mirror State

(Segment Piston = 93 nm)

- Error in segment piston from first measurement = 7.0 nm
- Error in segment piston after 2 iterations = 2.0 nm

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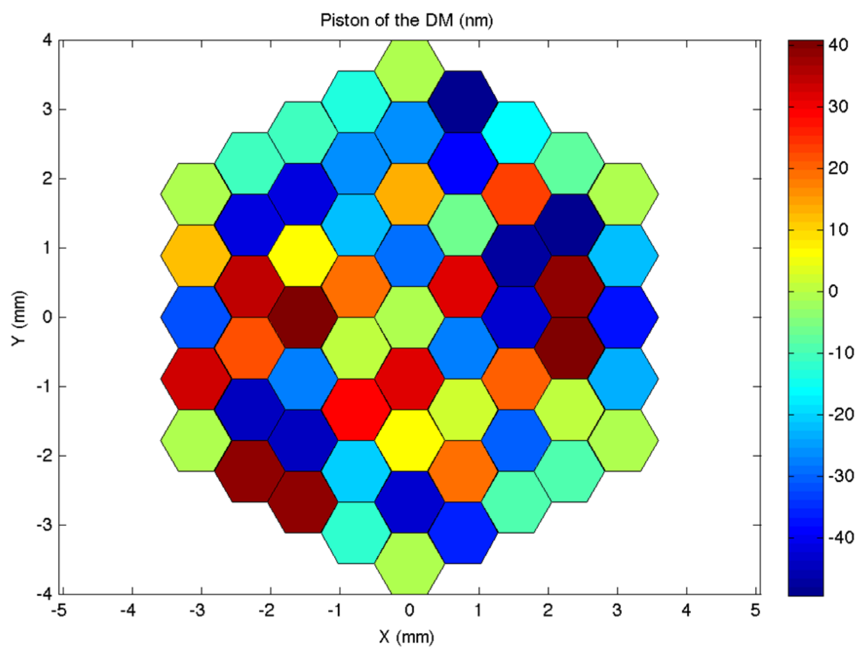
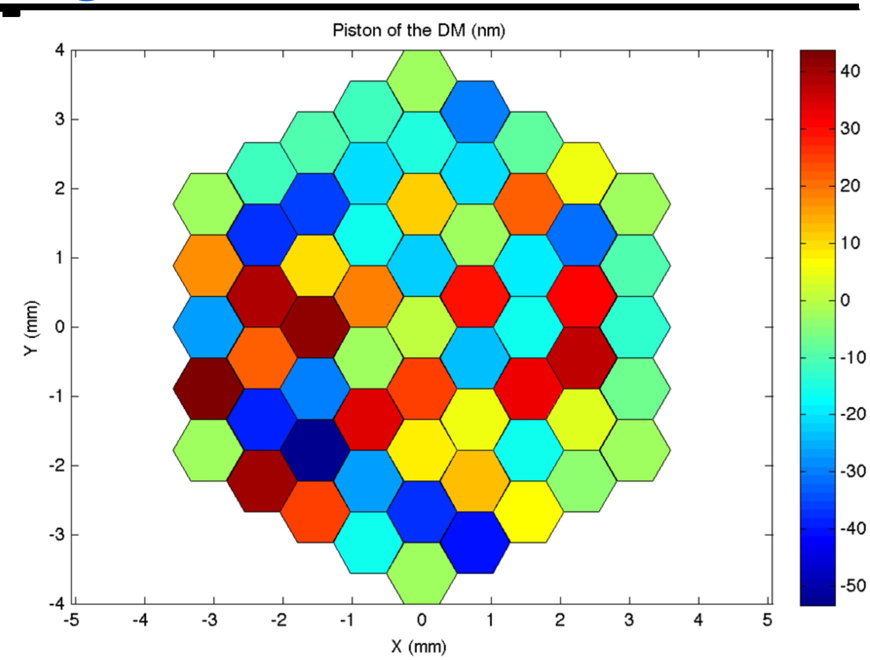
Measuring A Random Mirror Configuration



Applied Mirror State

(RMS = 29 nm)



Measured Mirror State

(RMS = 24 nm)

- RMS piston error of first measurement = 9.0 nm
- RMS piston error after sending 2 iterations times = 3.6 nm

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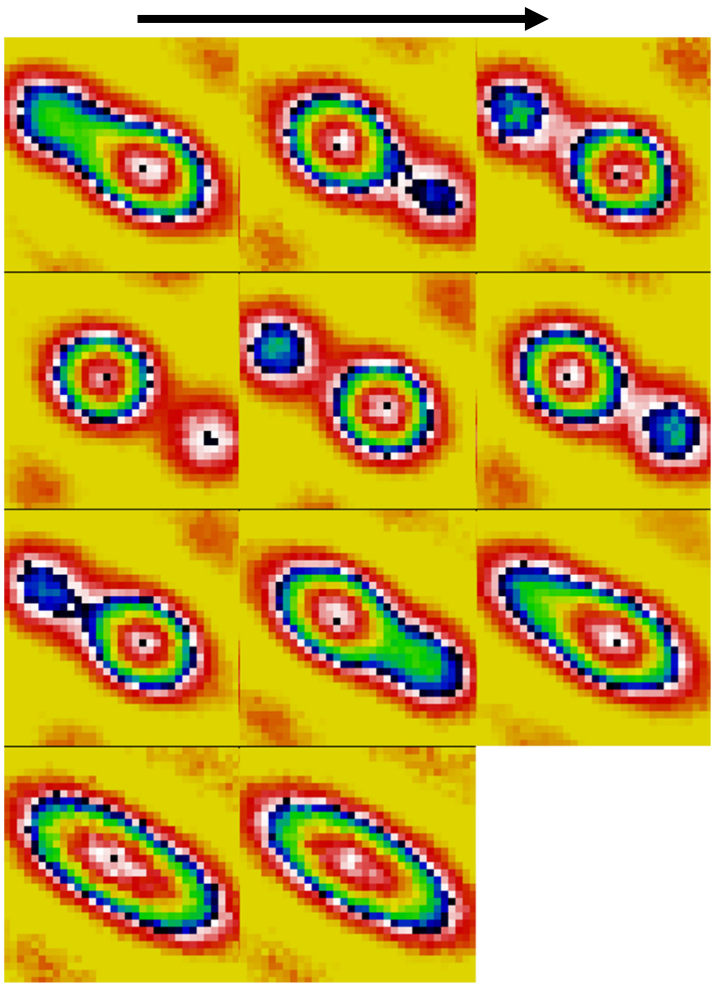
Coherence Phasing

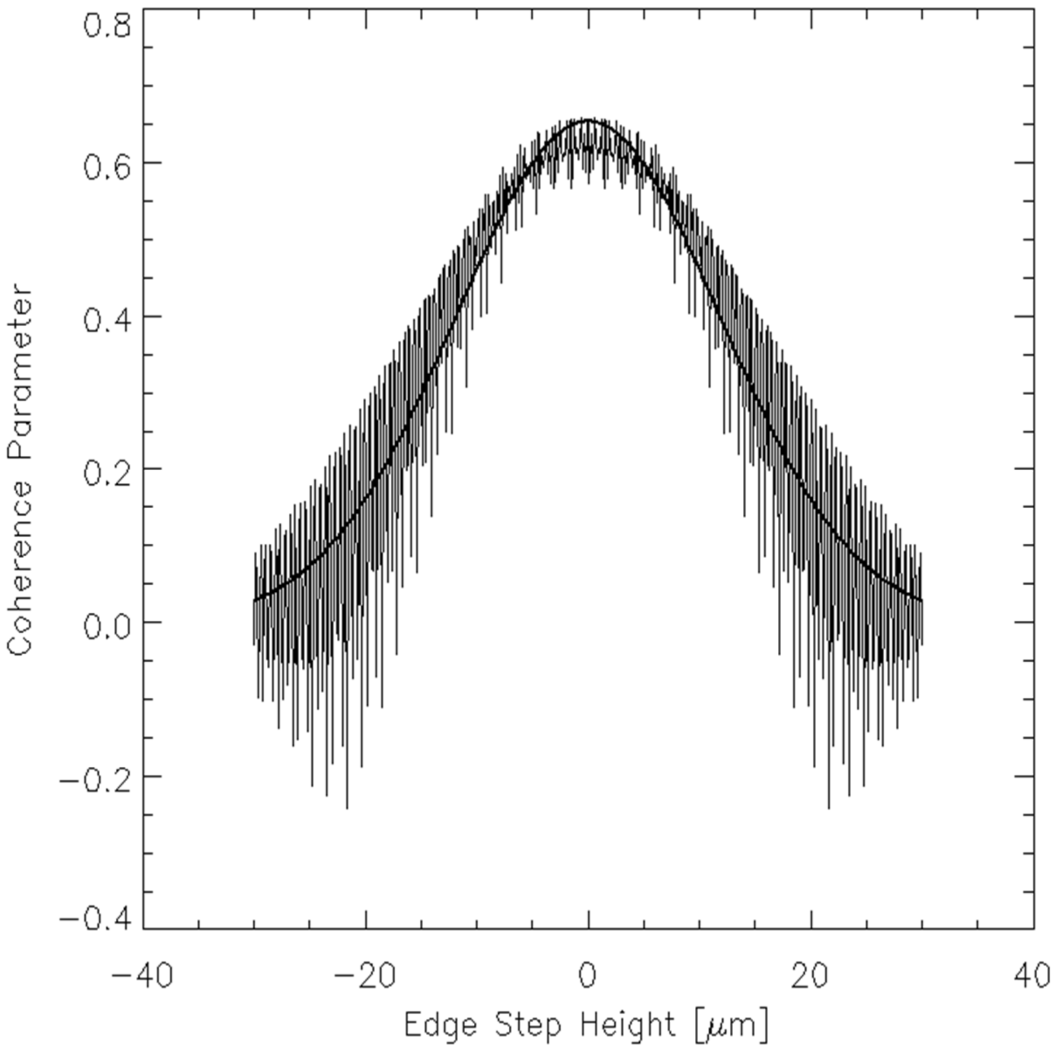
- Exploits the broadband nature of light
- When the phase step exceeds the coherence wavelength $\frac{\lambda^2}{2\Delta\lambda}$ the image becomes a superposition of multiple in-phase subimages resulting in an elongated sub-image
- We quantify this with the coherence parameter:
  - Maximum correlation – Minimum Correlation
- Each segment edge is stepped through 11 different phase steps and the coherence parameter calculated.
- The resulting coherence parameters are fit to a Gaussian and the edge step error calculated

Typical Broadband Sequence (Actual Keck Data)

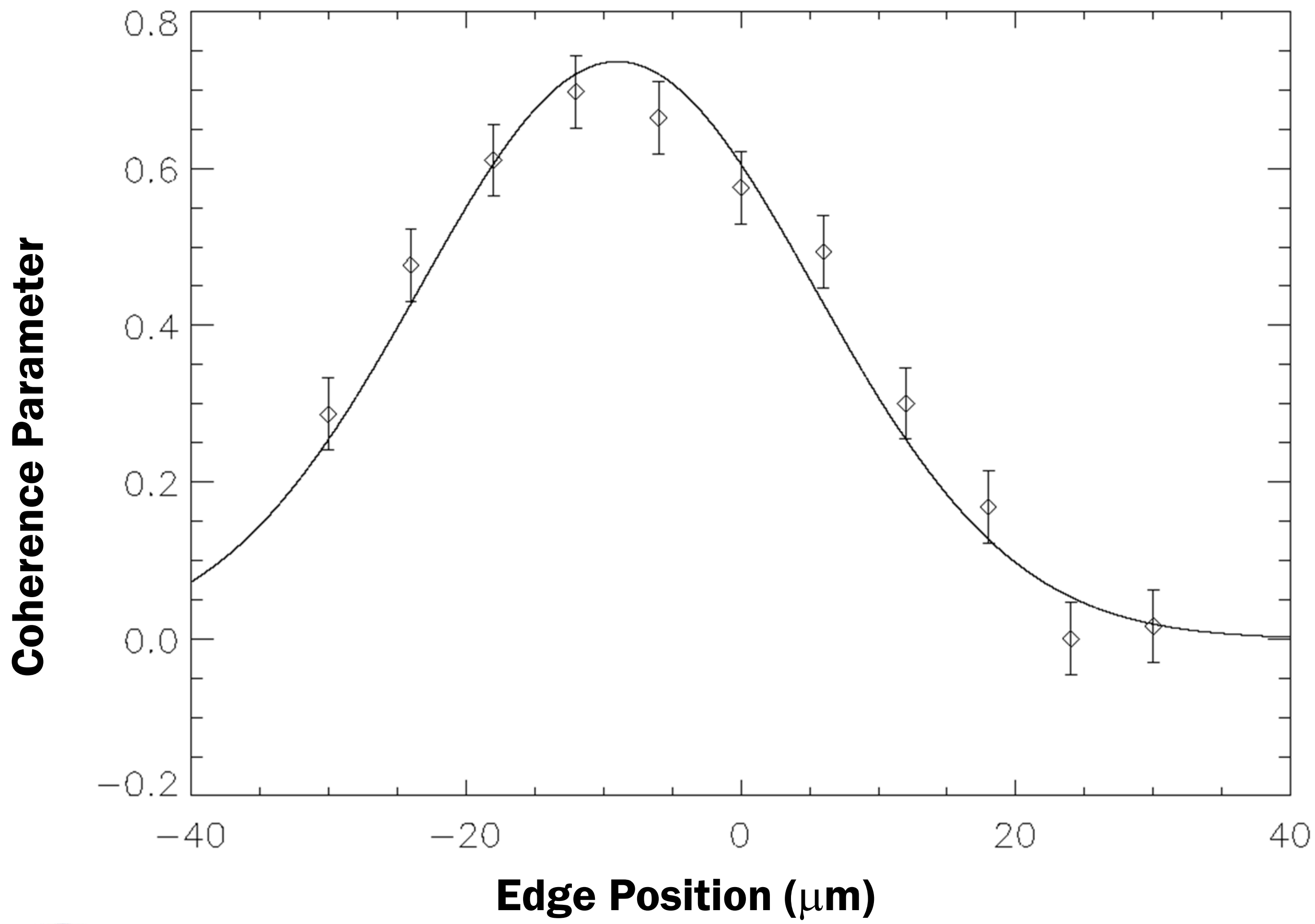


- Step Size = 6 µm
- Coherence Length = 40 µm
- (891/10 filter)

Coherence vs. Edge Step - Theory (891/10 nm)



Coherence vs. Edge Step – Keck Data (891/10 nm)

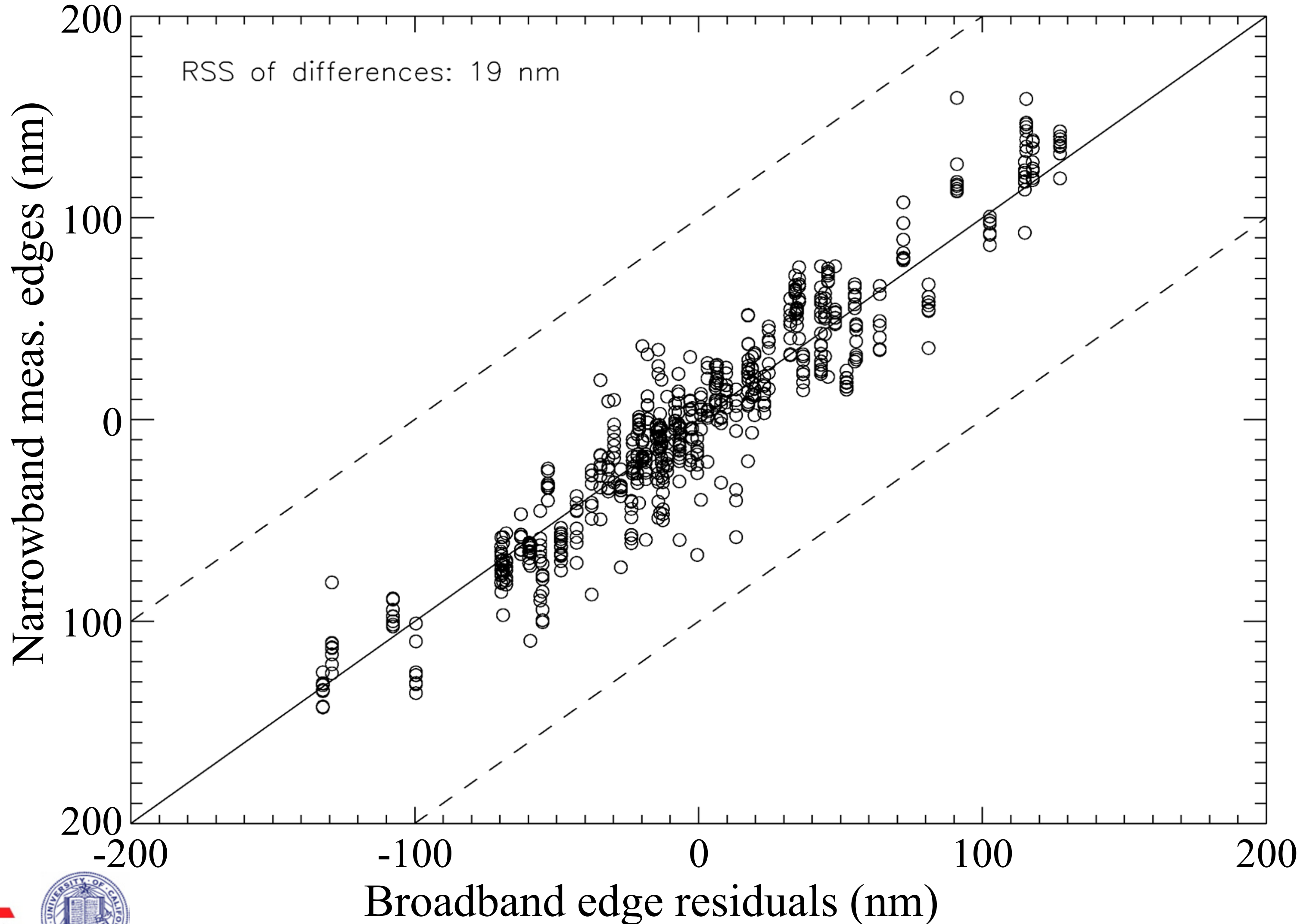


Broadband Phasing Parameters

Mode	Wave-length nm	Bandwidth nm	Coherence Length μm	Step Size μm	Accuracy nm	Capture Range μm	Star Magnitude V
Phasing-1000	891	10	40	6	1000	±30	4
Phasing-300	852	30	12	2	300	±10	5
Phasing-100	870	100	3.8	0.6	100	±3	6
Phasing-30	700 [eff]	200 [eff]	1.2	0.2	30	±1	7

- Capture range and accuracy for a specific application can be optimized by changing the number of steps and the coherence length of the filters used.

Narrowband vs. Broadband



Solving 2π Ambiguities: Coherence Length Is a Better Approach

- Synthetic Wavelength
  - Defined by $\frac{\lambda_1 \lambda_2}{\lambda_1 - \lambda_2}$
  - 30 μm to ¼ λ in 4-6 exposures
  - Highly sensitive to meas. Uncertainty
  - Gives wrong answer if out of range (see Lofdahl & Erikson)
  - Don't need to move segment
- Coherence Length
  - Defined by $\frac{\lambda^2}{2\Delta\lambda}$
  - 30 μm to ¼ λ in 22 exposures
  - Moderately sensitive to meas. Uncertainty
  - Gives no answer if edge step out of range
  - Must move segments
- Initial segment alignment errors and segment aberrations mean that edges are often out of range
- APE Experiments confirmed problems with artificial wavelengths
- Getting one edge wrong will "propagate" through the whole mirror
- The coherence technique essentially guarantees you don't get the wrong answer

Summary of Shack-Hartmann Phasing

- "Shack-Hartmann" phasing is routinely used for phasing of segmented telescopes
- Has a capture range that can exceed $\pm 30\ \mu m$
- Has an accuracy to better than 6 nm RMS
- Can work with both atmospheric and lab turbulence
- Is not sensitive to global aberrations
- Can be combined with a "normal" Shack-Hartmann camera
- Can support coherence length or artificial wavelength phasing

Acknowledgements

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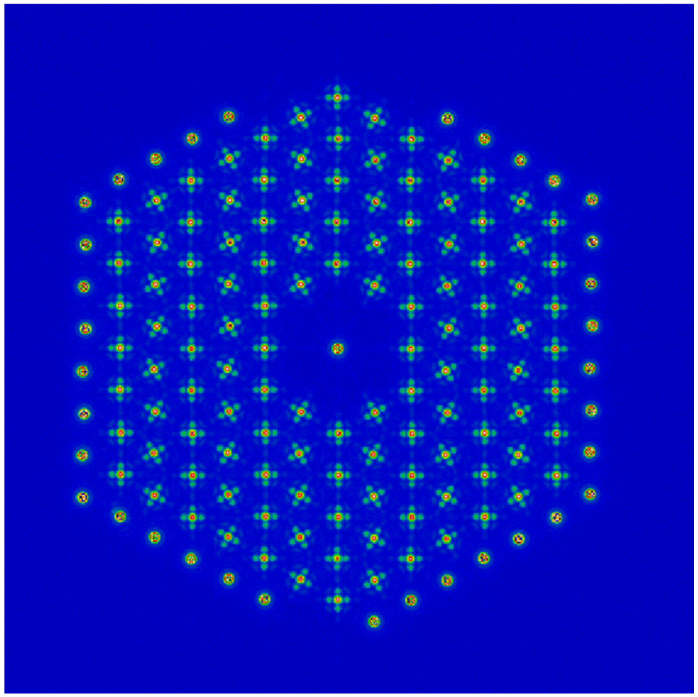
Backups

Phasing and Shack-Hartmann Cameras Have Somewhat Different Requirements

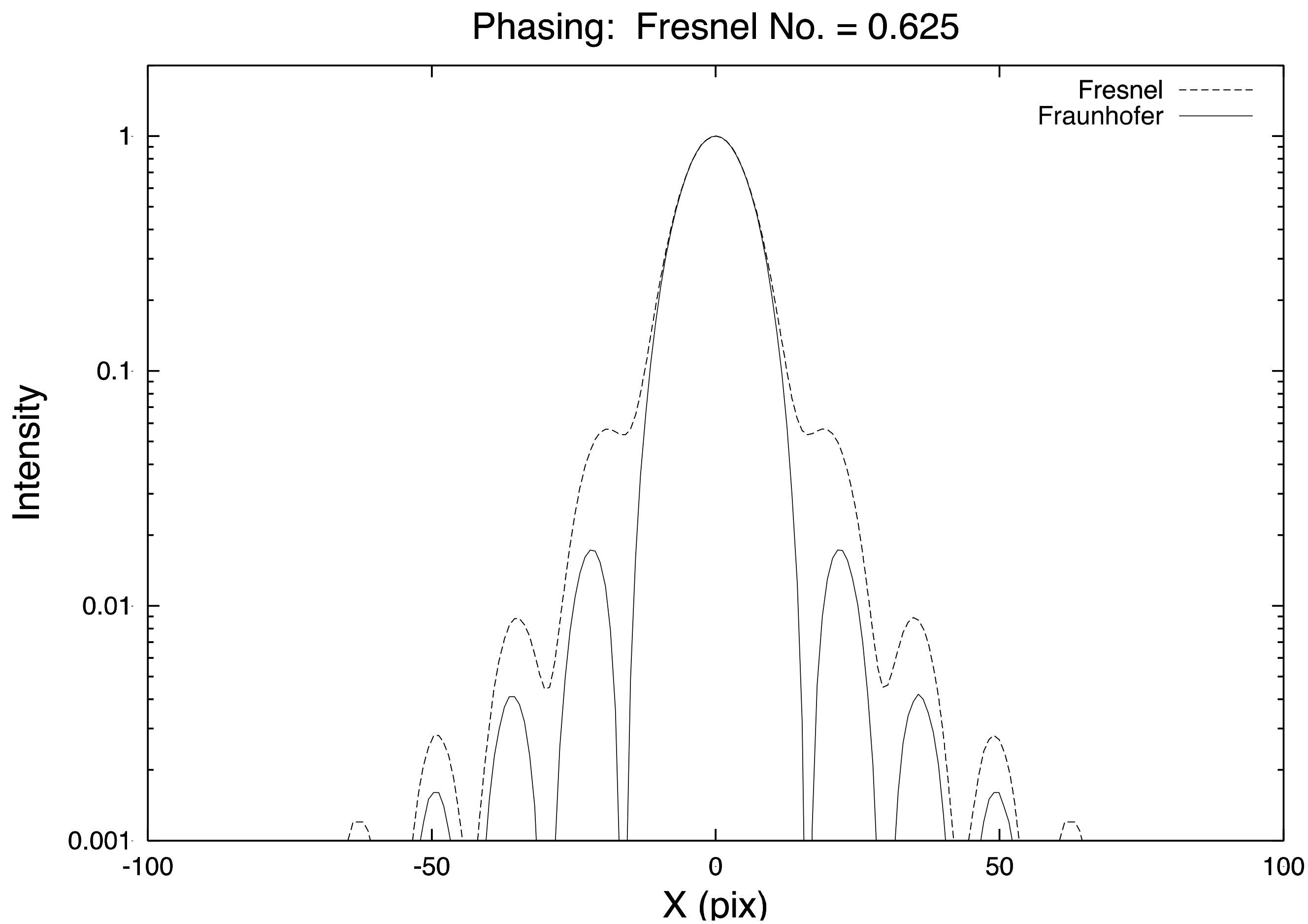
- Phasing requires a method to adjust the pupil location
  - Mask/Lenslet array should be on a stage
  - A piece of glass in the collimated beam that can be tilted
  - Accuracy is ~5% of a subaperture diameter
- The phasing camera re-imaged pupil must be of sufficient optical quality
- Focal plane plate scale:
  - Normal phasing: ~2 times Nyquist sampled images
  - Broadband phasing: ~4 times Nyquist sampled images

Keck Segment Phasing

- Optic: Array of micro-prisms
- Wavelength: 611 to 891 nm
- Star Mag: V = 4 to 8
- Capture Range:
  - BB +/- 30 microns
  - NB +/- 200 nm
- Accuracy:
  - BB +/- 30 nm
  - NB +/- 6 nm



Fresnel vs. Fraunhofer: In-Phase Segments



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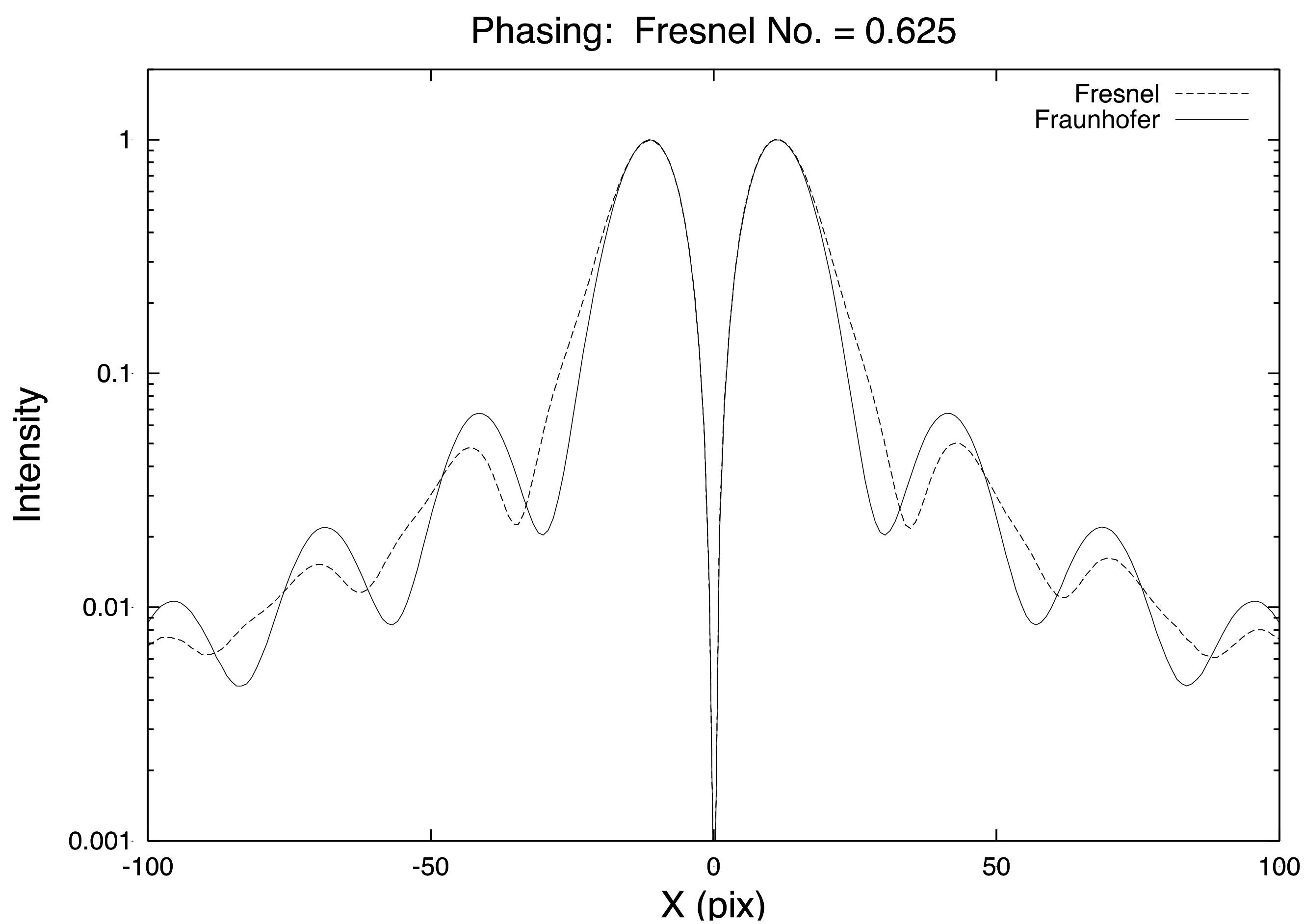
Fresnel vs. Fraunhofer: Out-of-Phase Segments



•Phasing Reference Beam

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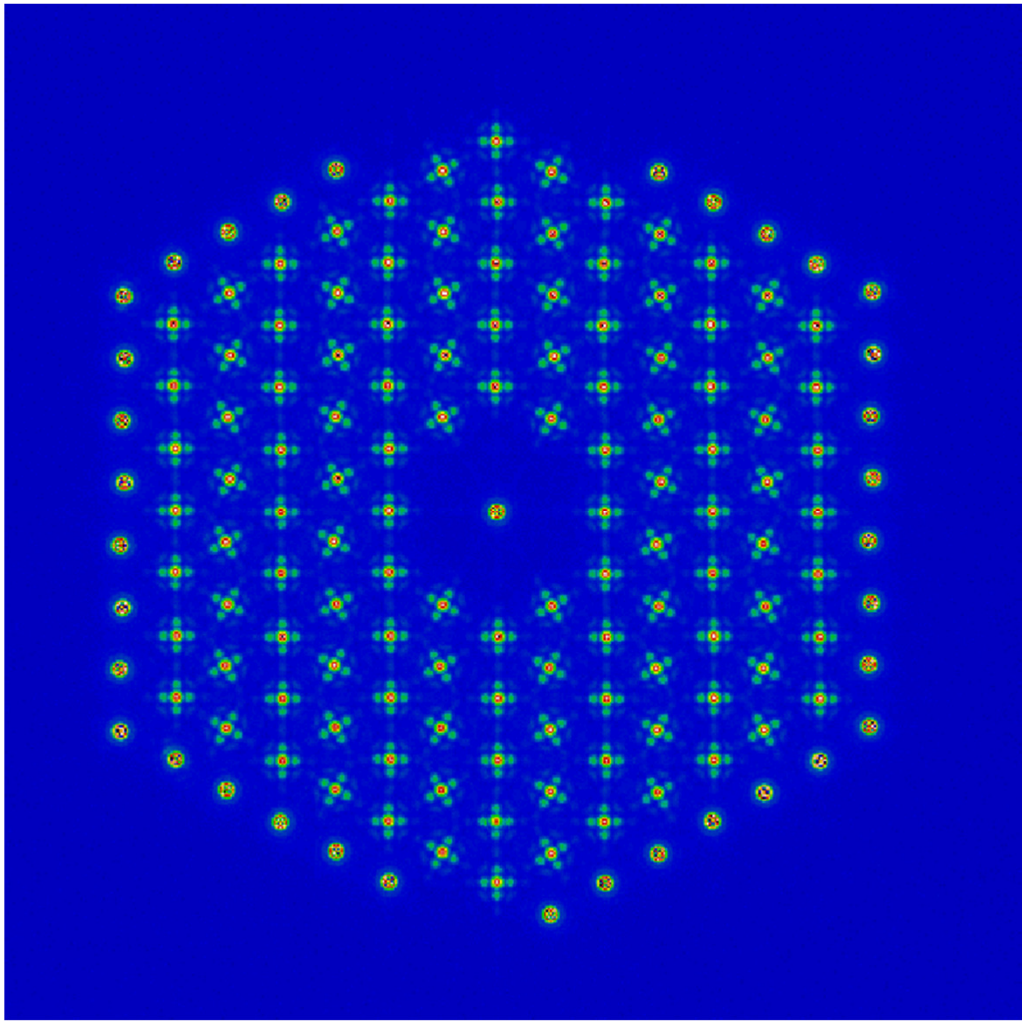
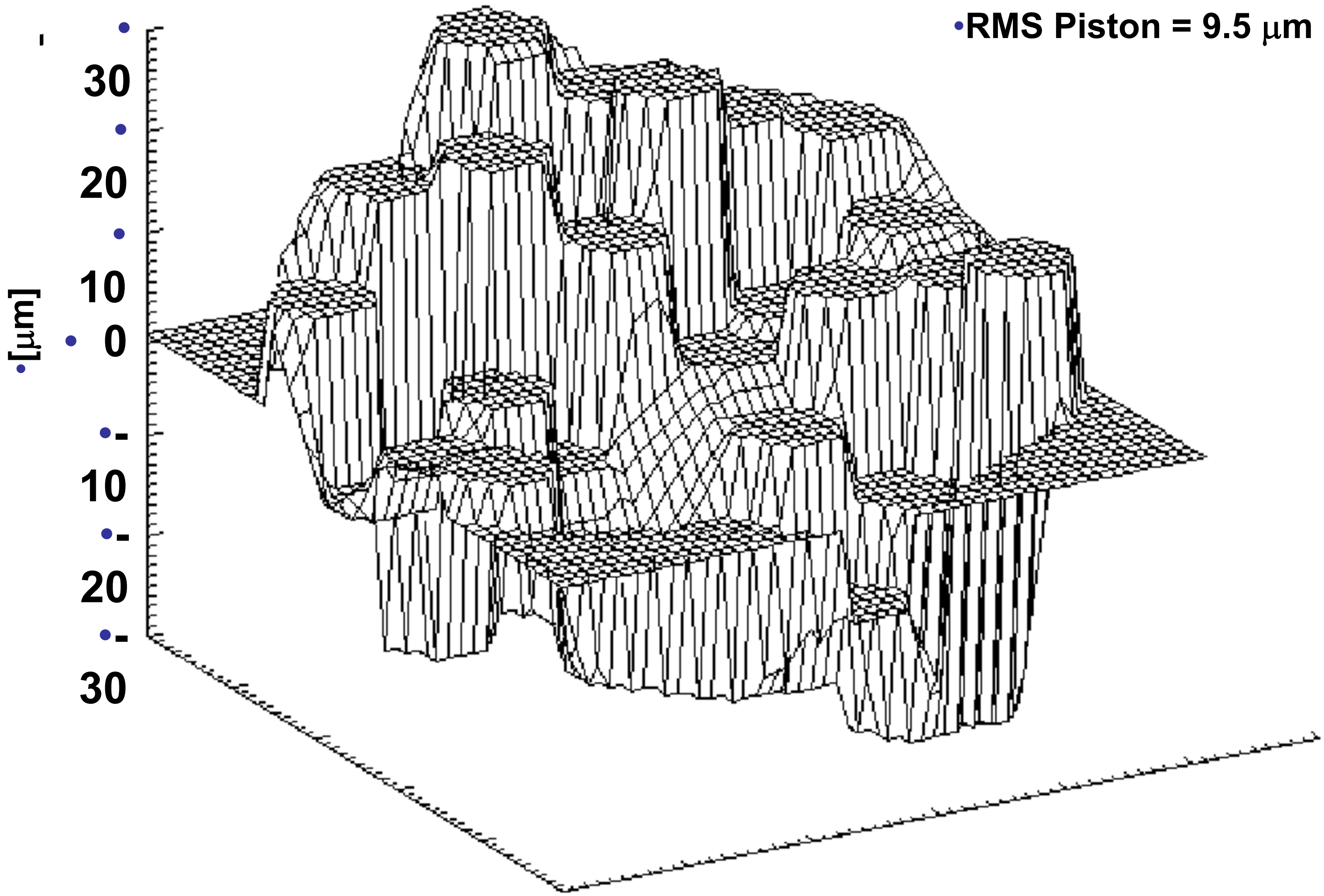


Primary Mirror Phase Error First Light (Keck II)

- March 12, 1996
- RMS Piston = 9.5 μm



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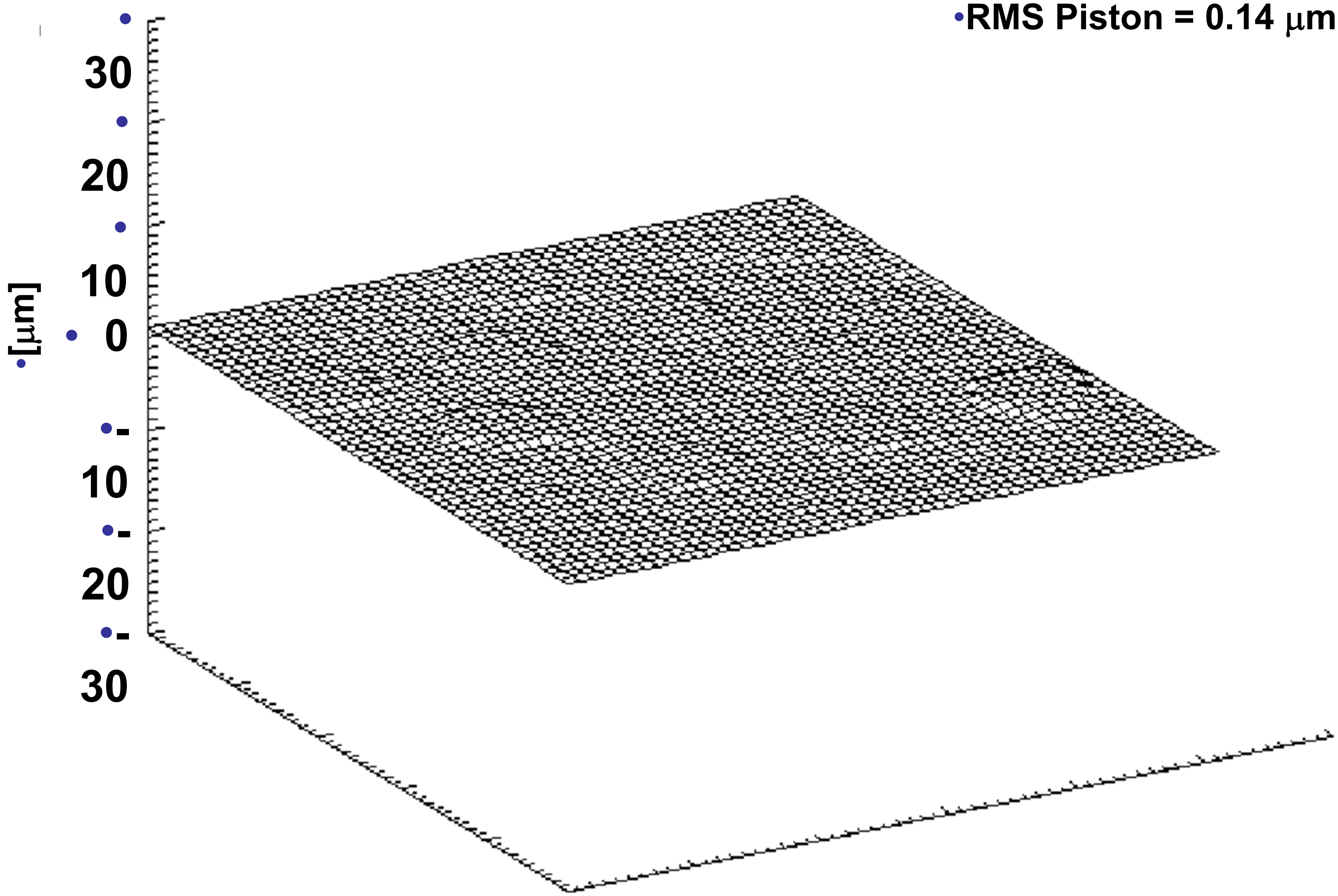
Primary Mirror After Broadband Phasing

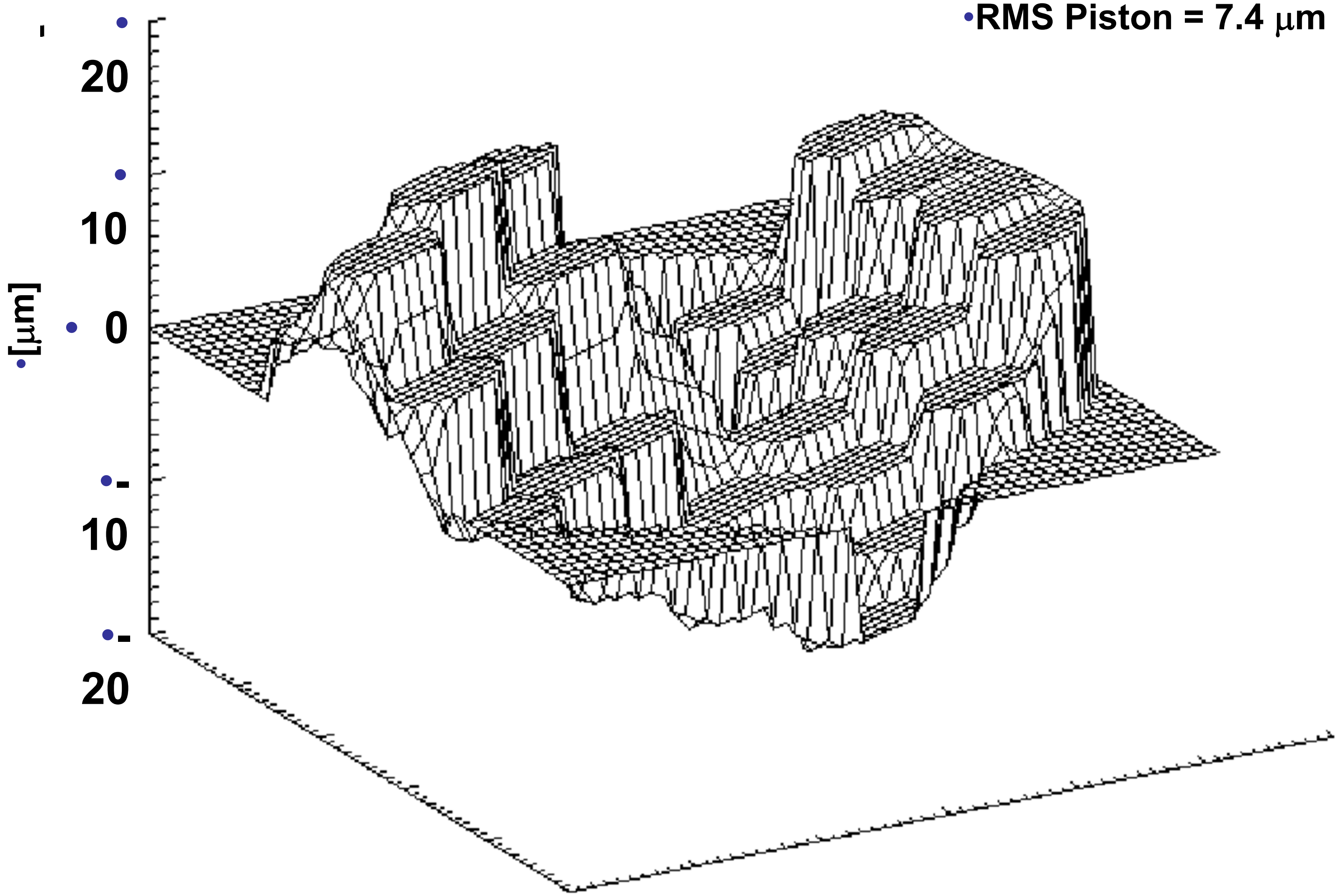
- March 14, 1996
- RMS Piston = 0.14 μm



•Primary Mirror Phase Error First Light (Keck II)

•June 14, 1996

•RMS Piston = 7.4 μm



•Primary Mirror After Phasing

•June 14, 1996

•RMS Piston = 0.025 μm