Megapixel Adaptive Optics

Towards Correcting Large-scale Distortions in Computational Cameras

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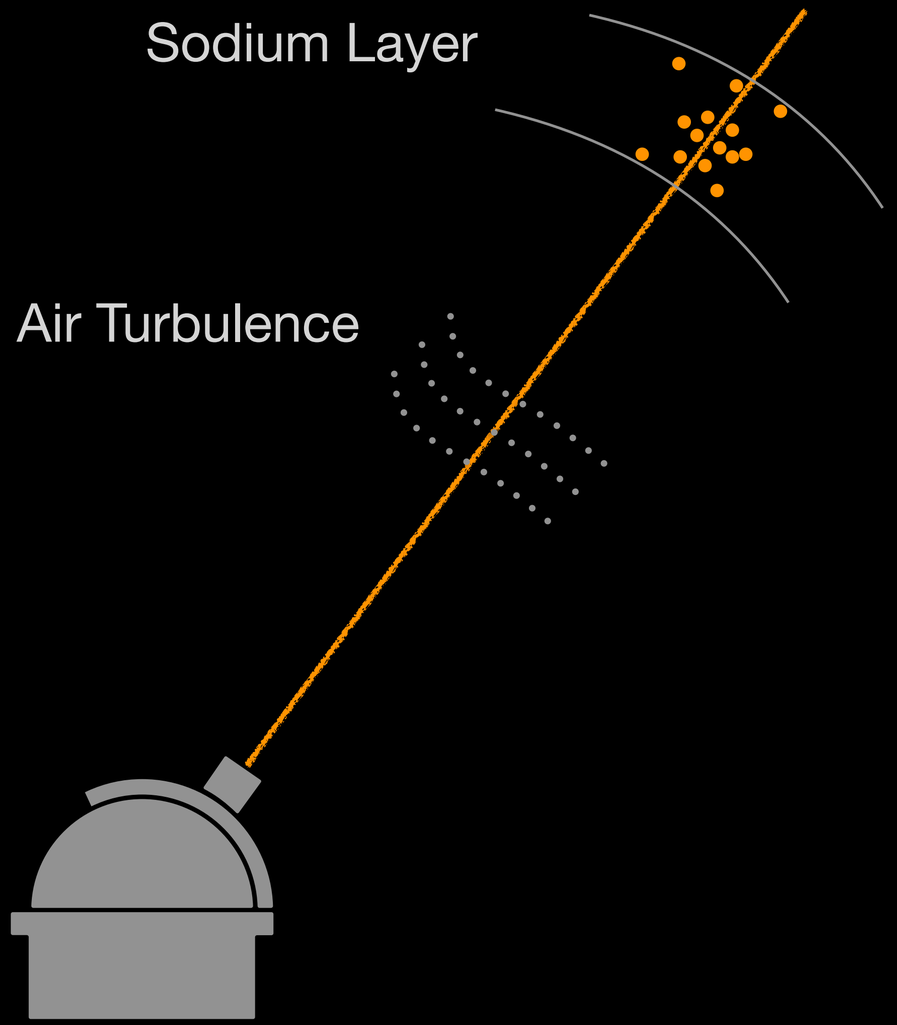
Adaptive Optics

Twinkle Stars

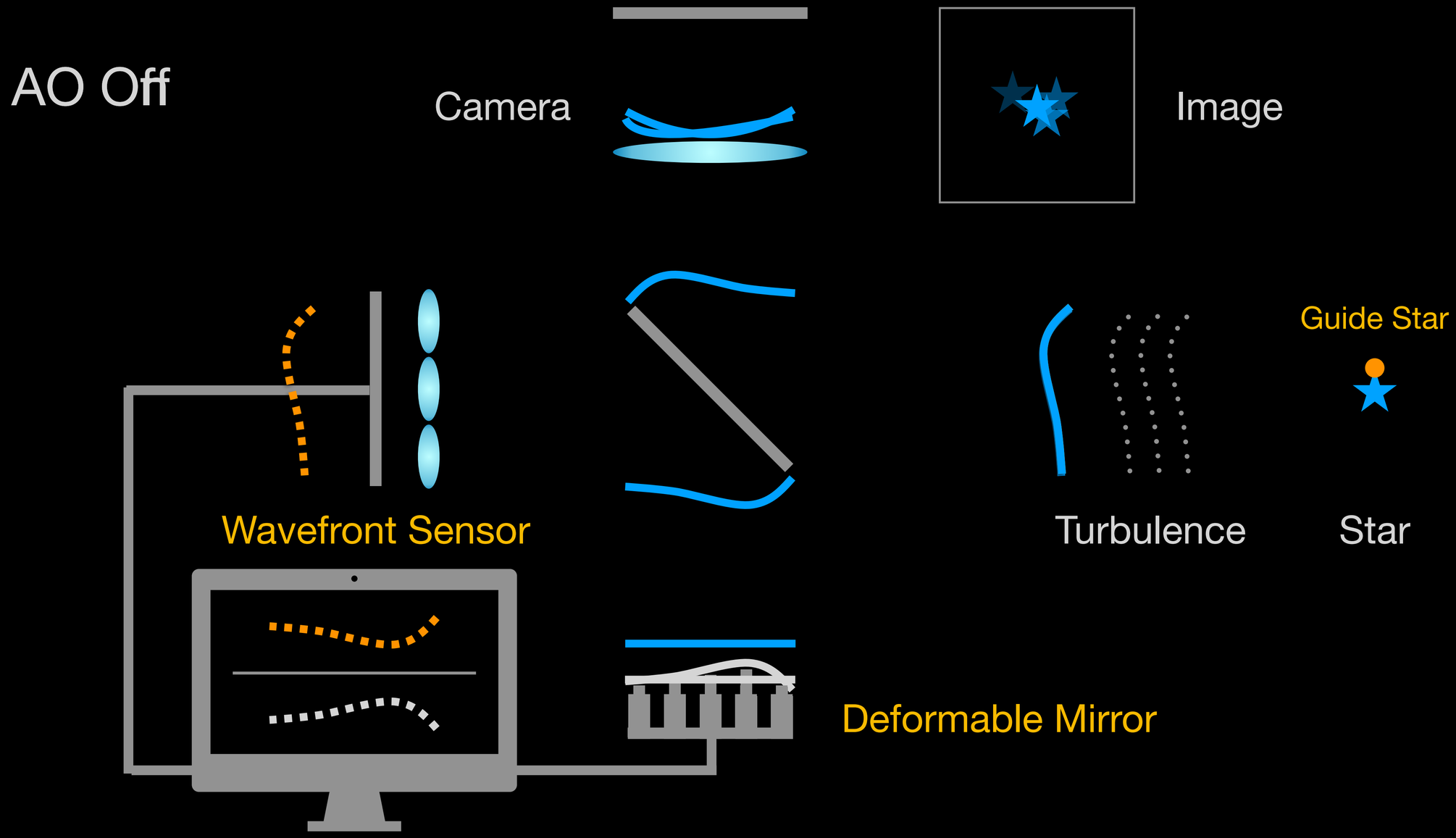
Heat Haze Effect

[https://youtu.be/DMwcGUUUhYU, Sydney Airport (Kingsford-Smith) Runway 34L]

Adaptive Optics — Basic Principle

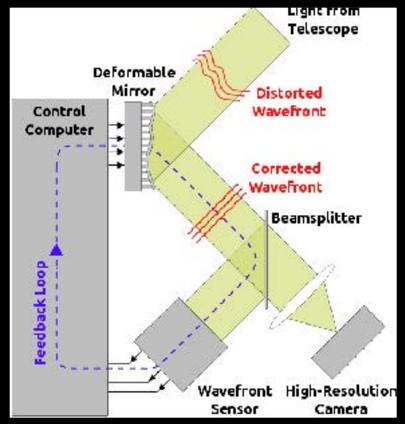


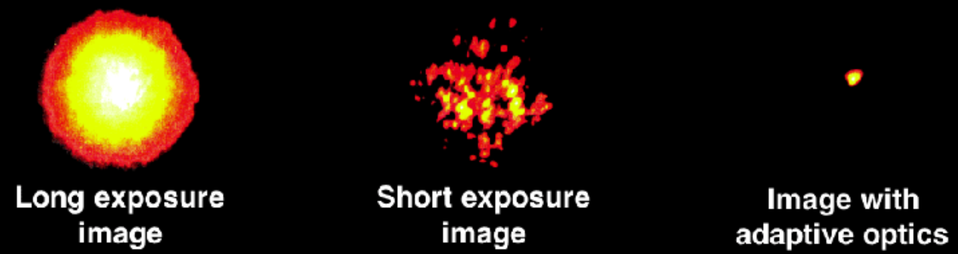
Adaptive Optics — Basic Principle



Applications of Adaptive Optics

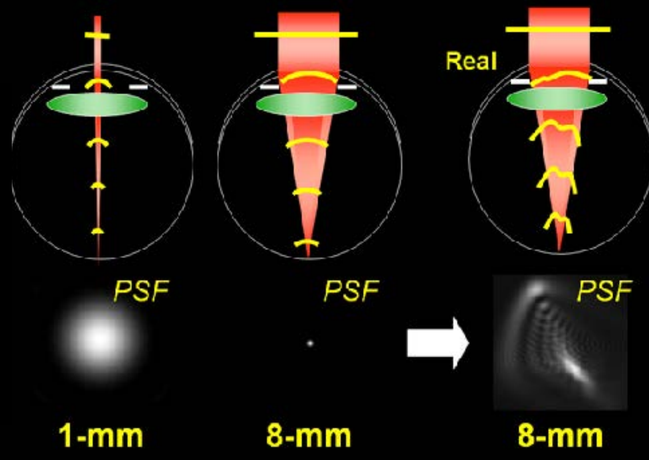
Astronomy





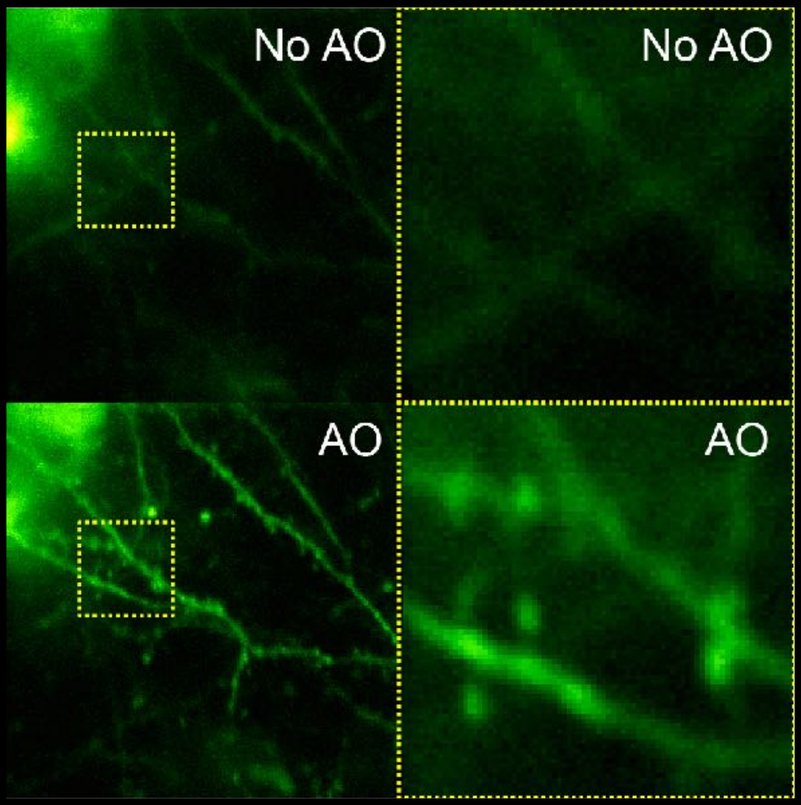
NSF Center for Adaptive Optics

Ophthalmology



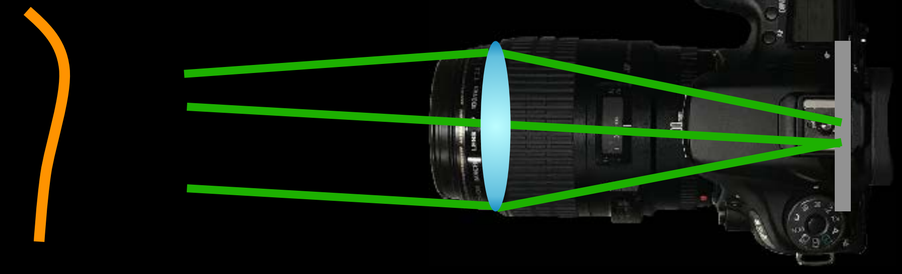
Retinal imaging with AO

Microscopy



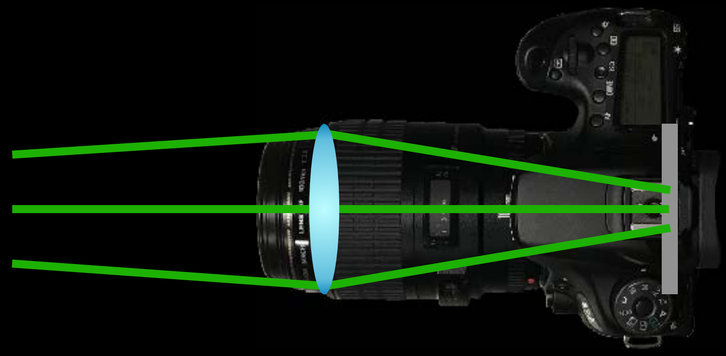
Florescence microscopy with AO

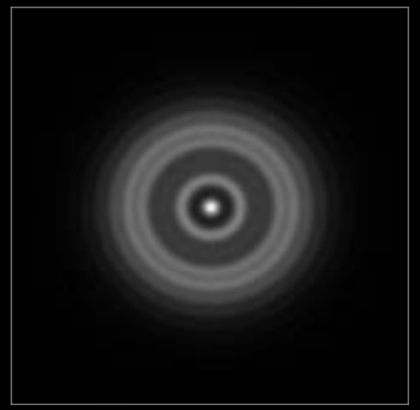
Image Formation in Vision Cameras



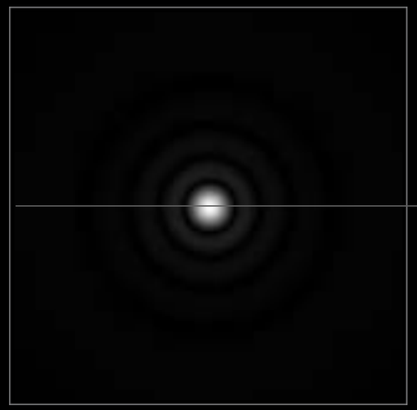
Object Wavefront Lens Sensor Image

Image Formation in Vision Cameras

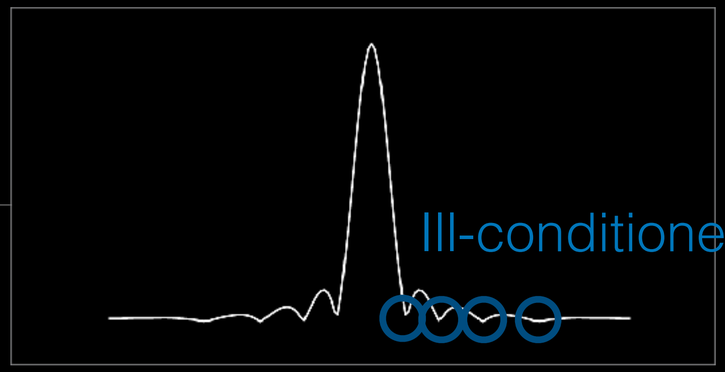




PSF
(Spatial domain)



OTF
(Frequency domain)

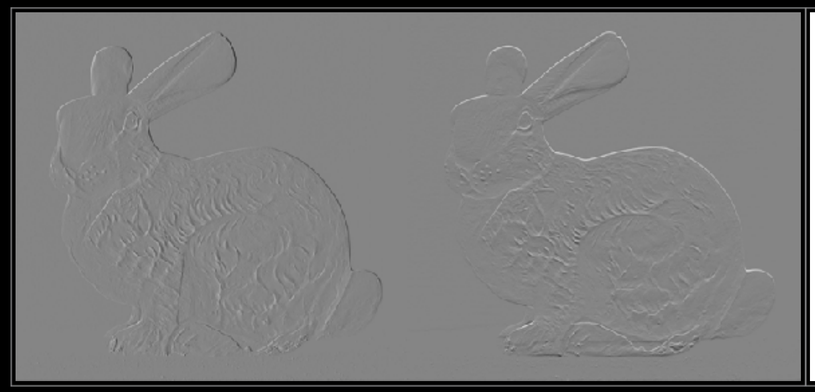


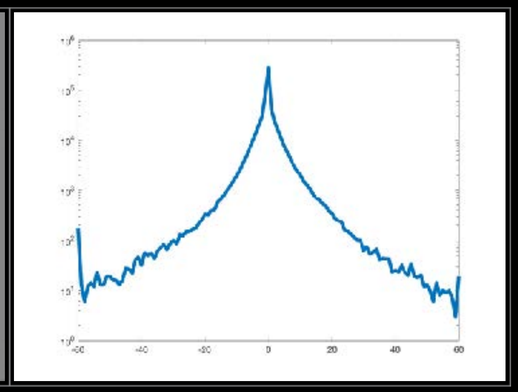
OTF cross section

Current Deblurring Approaches

Passive Deconvolution

Priors + PSF Shaping





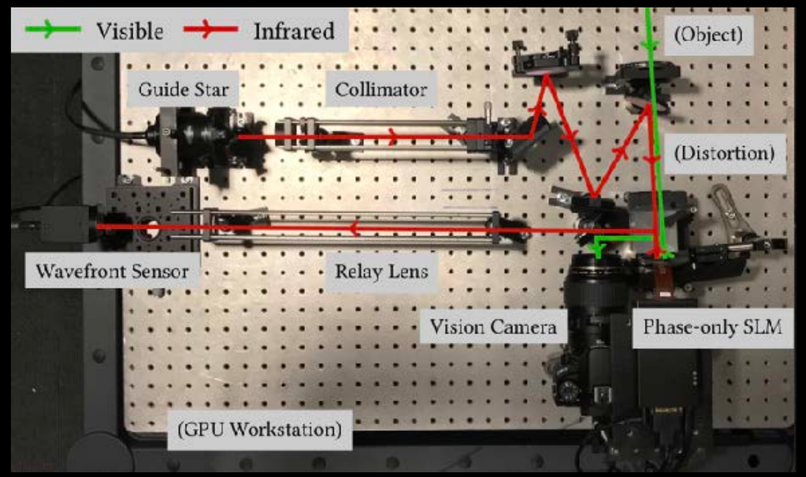
Natural Image Priors

Coding Component

Adaptive Optics for Vision Deblurring

Active Deconvolution

Adaptive Optics



AO Setup

Active Correction (Ours)

Traditional AO Systems: Components

- 100~1000 actuators
- 1 kHz frame rate

Deformable Mirror

- <1000 sub-apertures
- 0.1~1 kHz frame rate

Shack-Hartmann Wavefront Sensor

Megapixel AO System: Components

- 1920 x 1080 pixels
- 60 Hz input frame rate

[PLUTO-2-VIS-014-C, Holoeye]

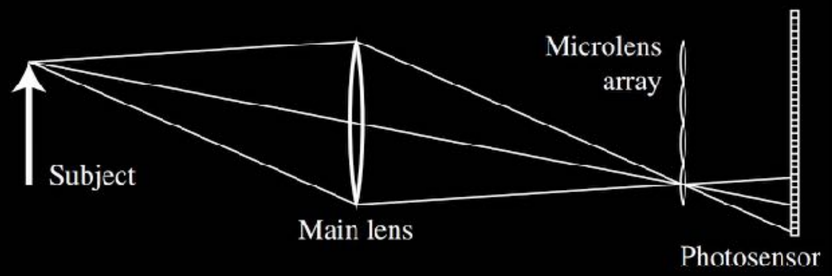
Spatial Light Modulator

- 1024 x 1024 pixels
- Video-frame rate

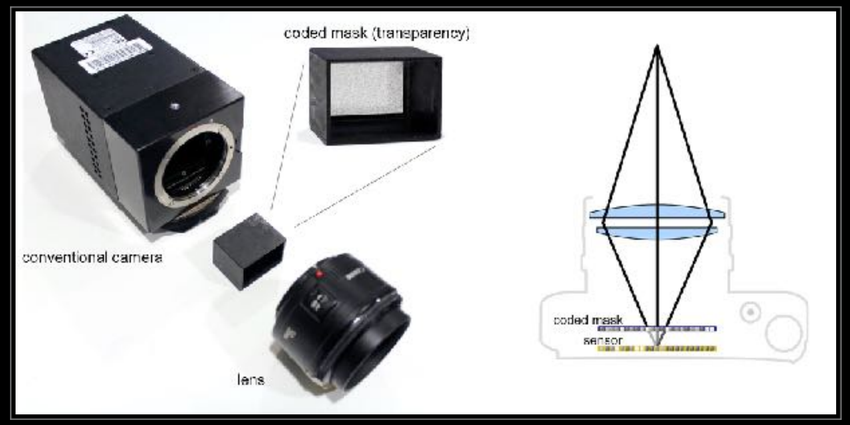
Coded Wavefront Sensor

[Wang et al. 2017]

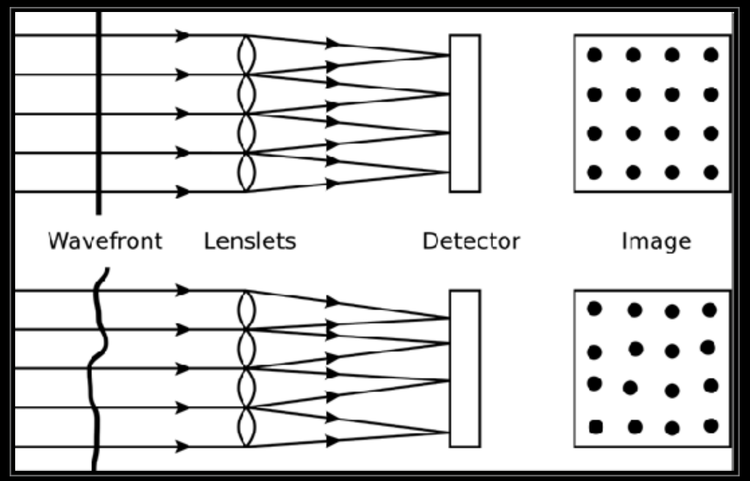
Coded Wavefront Sensor: Analogy



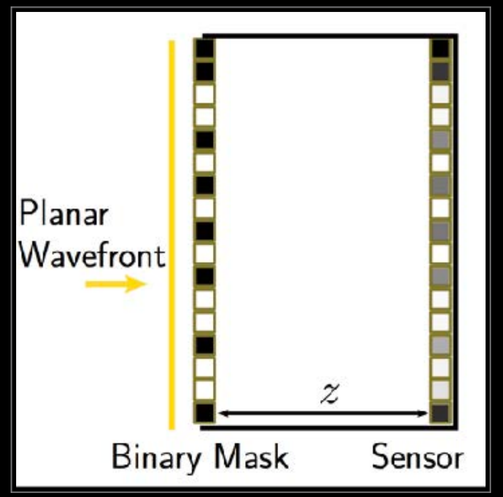
Lenslet light field camera
[Ng et al. 2005]



Mask-based light field cameras
[Veeraraghavan et al. 2007, Marwah et al. 2013]

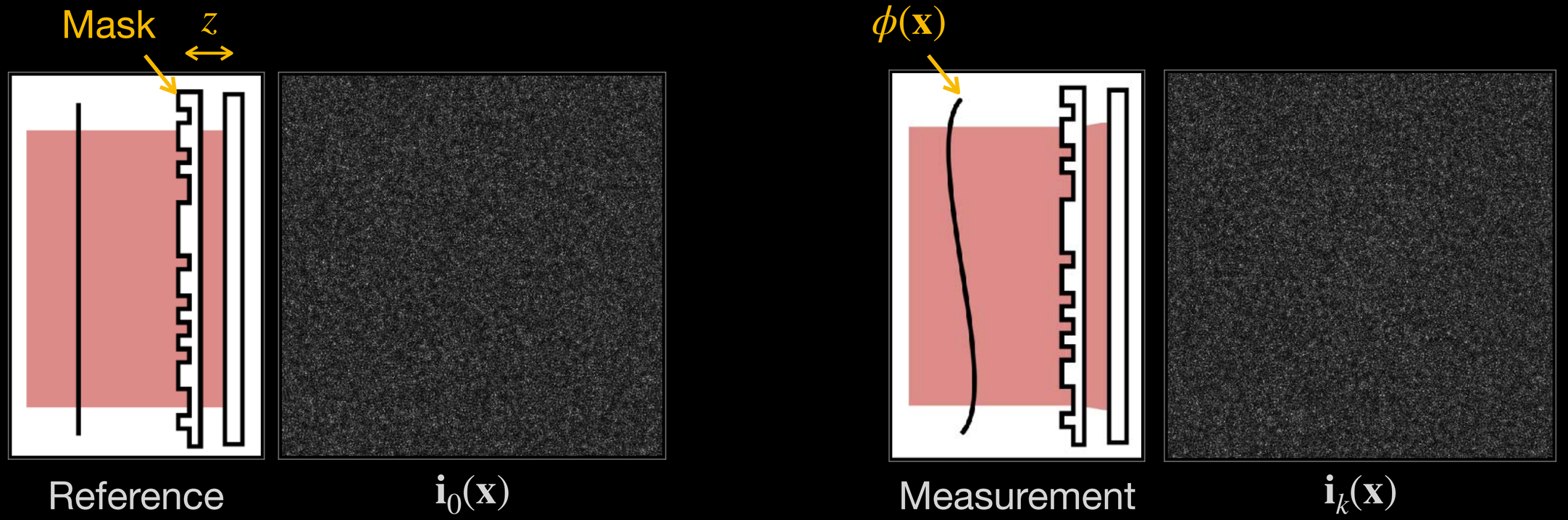


Shack-Hartmann wavefront sensor
[Shack and Platt 1971]



Coded wavefront sensor
[Wang et al. 2017]

Coded Wavefront Sensor: Principle



$$\mathbf{i}_k(\mathbf{x}) \approx \mathbf{i}_0\left(\mathbf{x} - \frac{\lambda z}{2\pi}\nabla\phi(\mathbf{x})\right)$$

[Wang et al. 2017]

wavefront slope as “optical flow”

λ wavelength

z distance

Coded Wavefront Sensor: Principle

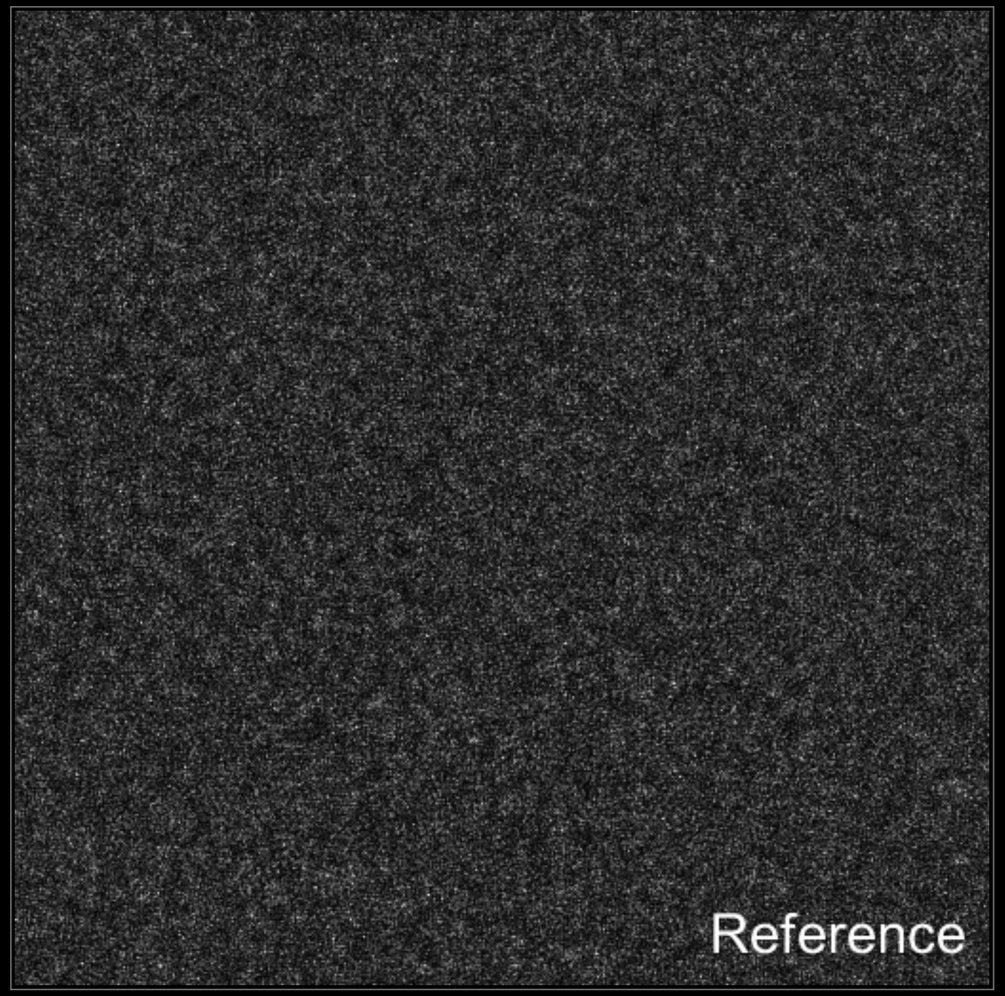
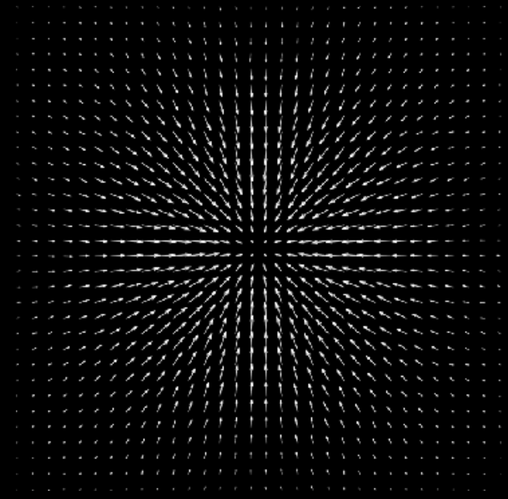


Image pair (simulated)

Curl-free optical flow

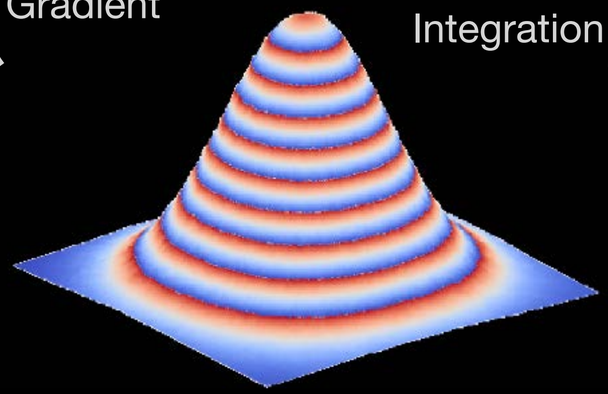


$\nabla\phi(\mathbf{x})$

Wavefront slope

Gradient

Poisson Integration



$\phi(\mathbf{x})$

Wavefront

Algorithm: Curl-free Optical Flow

Nonlinear Least Squares:

$$\underset{\boldsymbol{\phi}}{\text{minimize}} \quad \underbrace{\left\| \mathbf{i}_k(\mathbf{x}) - \mathbf{i}_0\left(\mathbf{x} - \nabla\boldsymbol{\phi}\right) \right\|_2^2}_{\text{Model Fitting}} + \underbrace{\beta \left\| \nabla\boldsymbol{\phi} \right\|_2^2}_{\text{Smoothness Prior}}$$

Linear Least Squares + Warping:

$$\underset{\delta\boldsymbol{\phi}}{\text{minimize}} \quad \left\| \underbrace{\nabla\mathbf{i}_k(\mathbf{x})}_{\text{Spatial Gradient}} \cdot \nabla(\delta\boldsymbol{\phi}) + \underbrace{\mathbf{i}_k(\mathbf{x}) - \mathbf{i}_0(\mathbf{x} - \nabla\boldsymbol{\phi}^j)}_{\text{"Temporal" Gradient}} \right\|_2^2 + \beta \left\| \nabla(\delta\boldsymbol{\phi}) \right\|_2^2$$

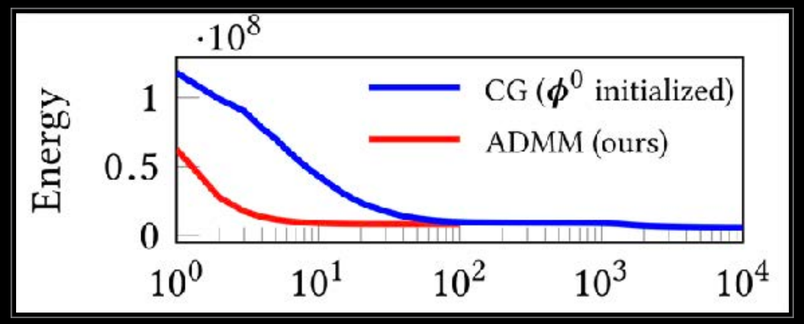
(Warping) ↓ (Linearization)

Loop $j = j + 1$

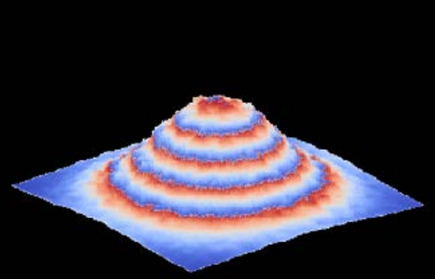
$$\boldsymbol{\phi}^{j+1} = \boldsymbol{\phi}^j + \delta\boldsymbol{\phi}$$

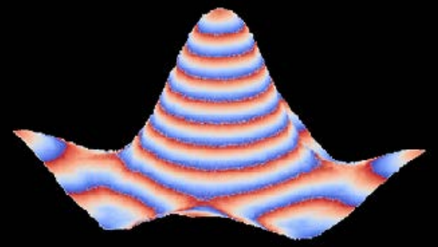
(Accumulation)

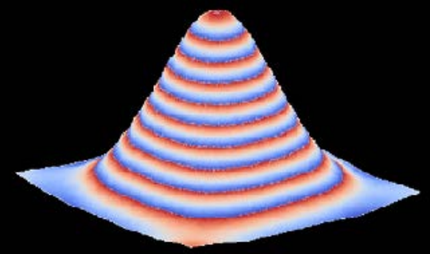
Algorithm: Linear Solver Comparison

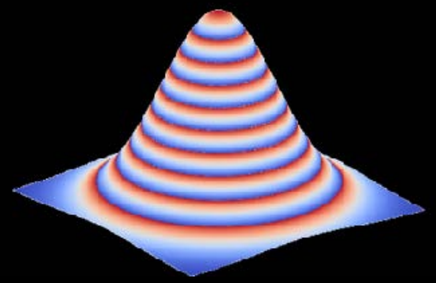


CG (initialized)

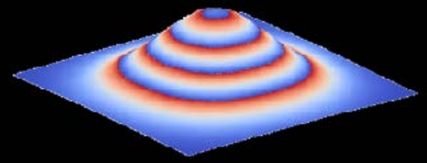

Iter = 1

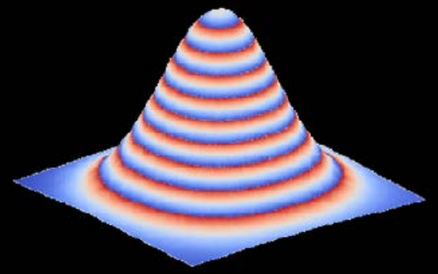

Iter = 500

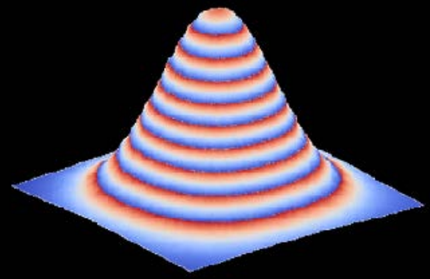

Steady


Ground Truth

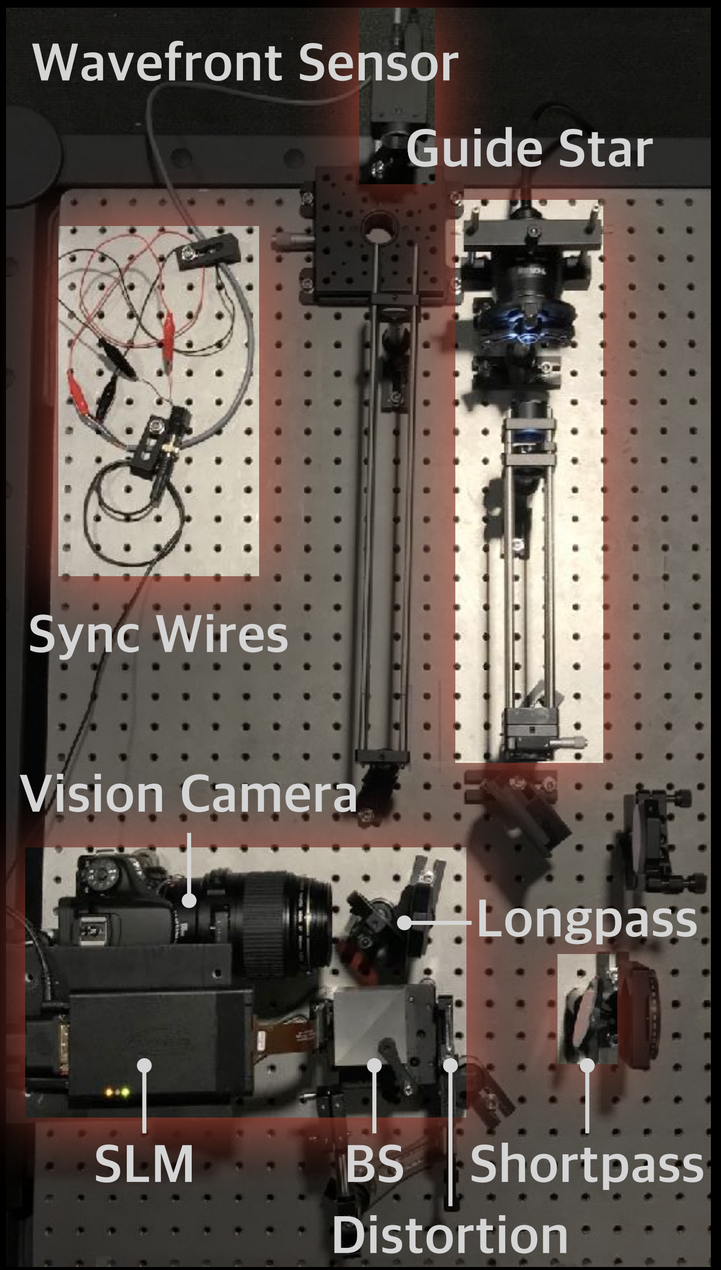
ADMM (ours)

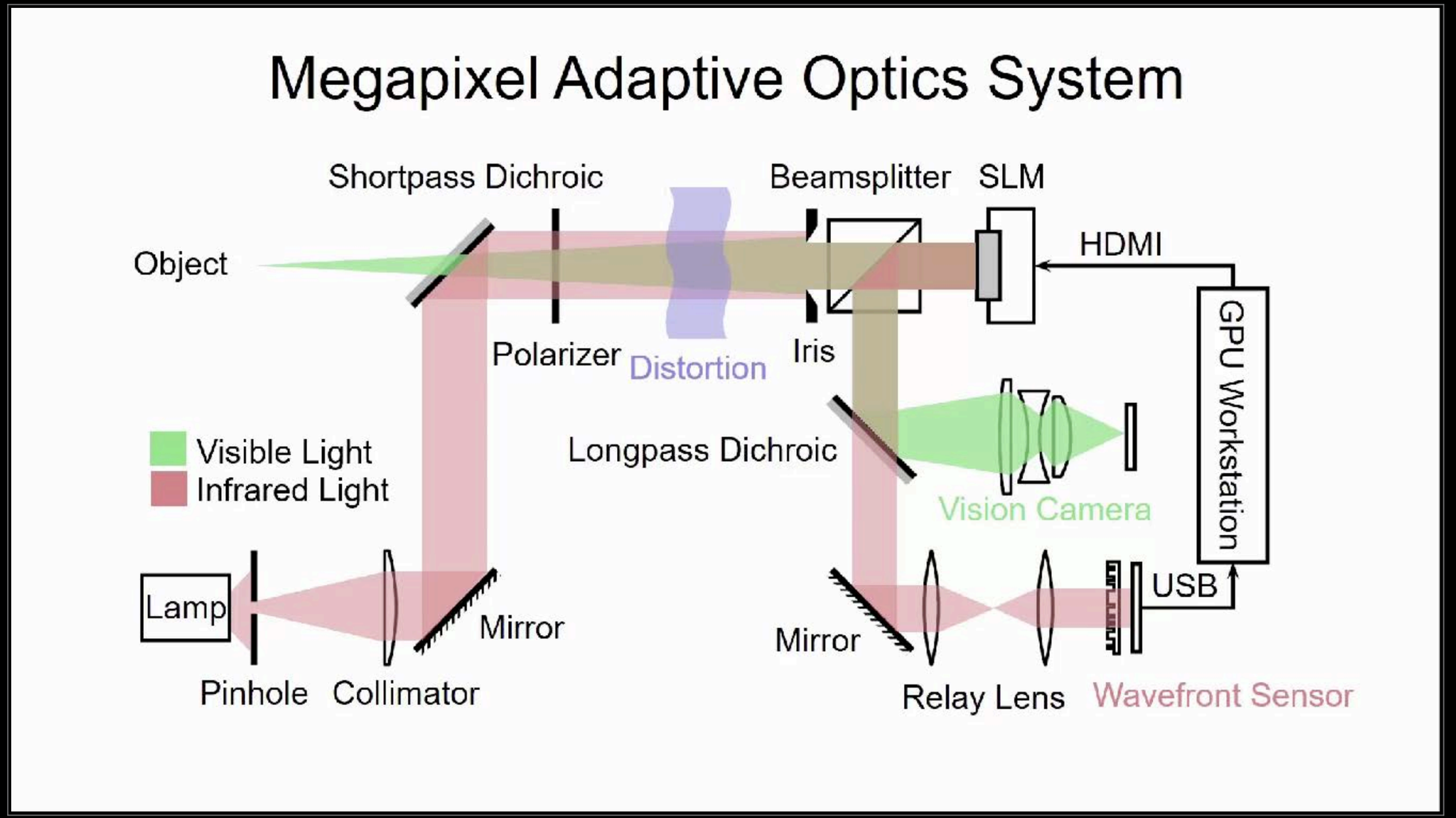

Iter = 1


Iter = 10

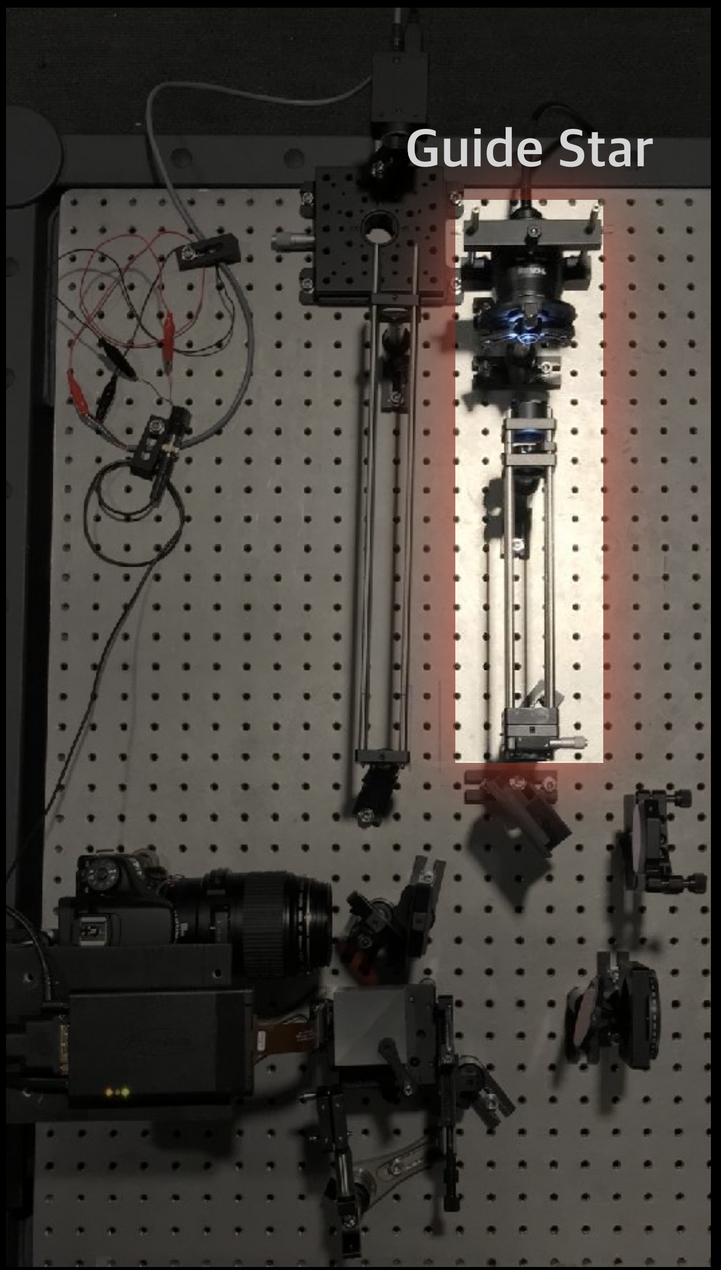

Steady

Implementation: Optical Setup

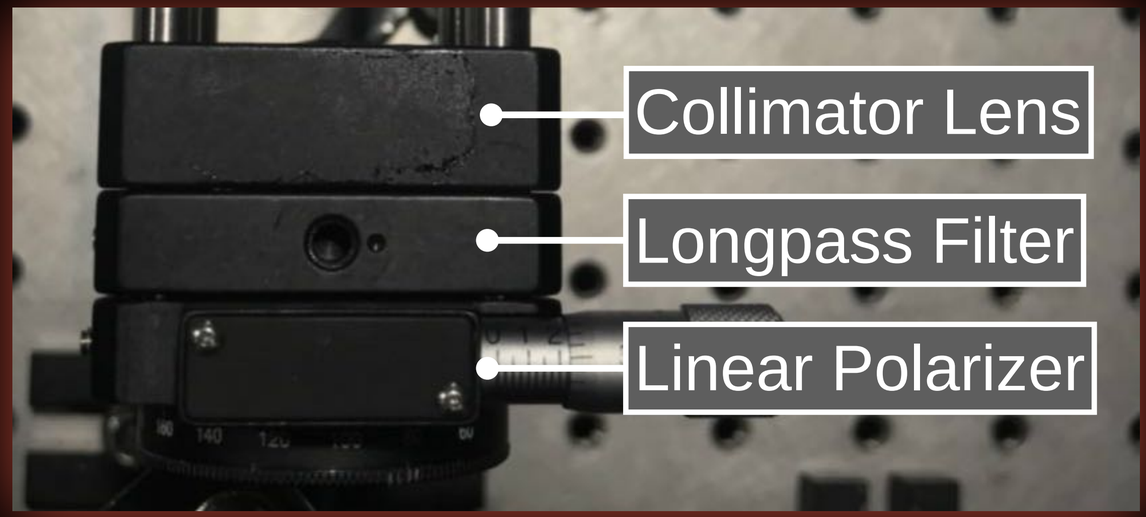




Implementation: Optical Setup



Infrared Collimated Illumination

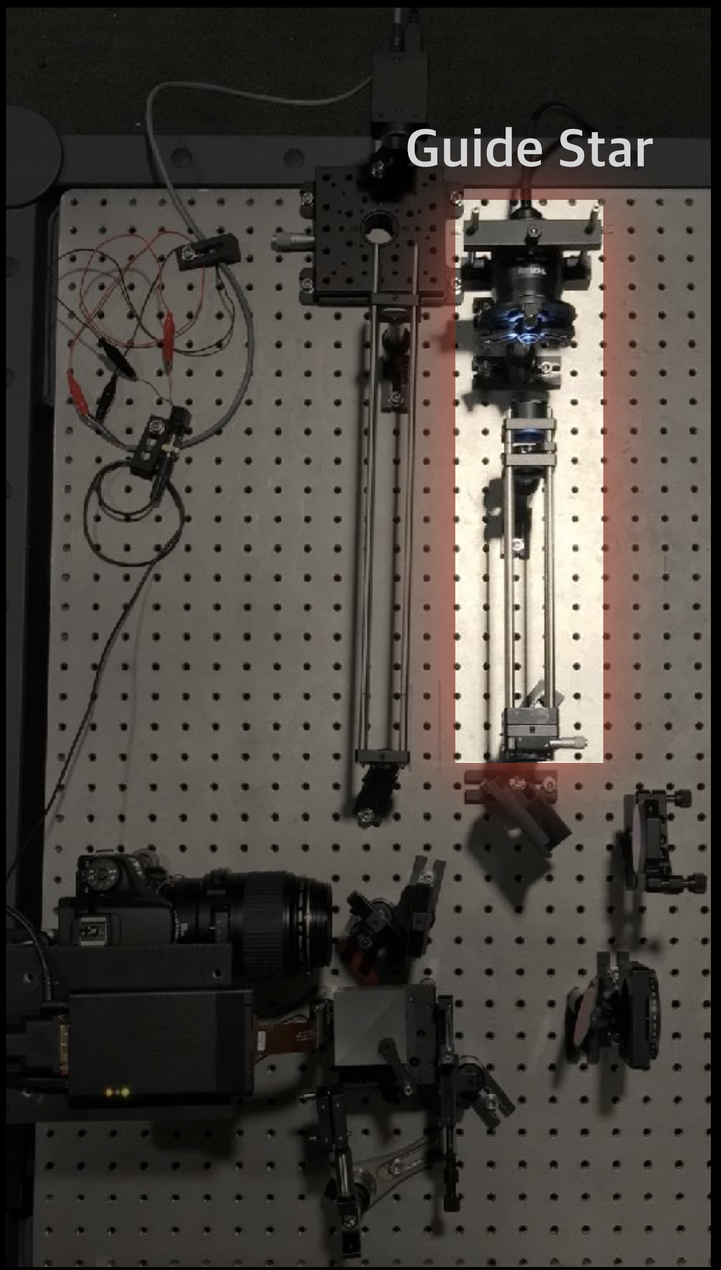


[AC254-200-A, Thorlabs]

[FEL0700, Thorlabs]

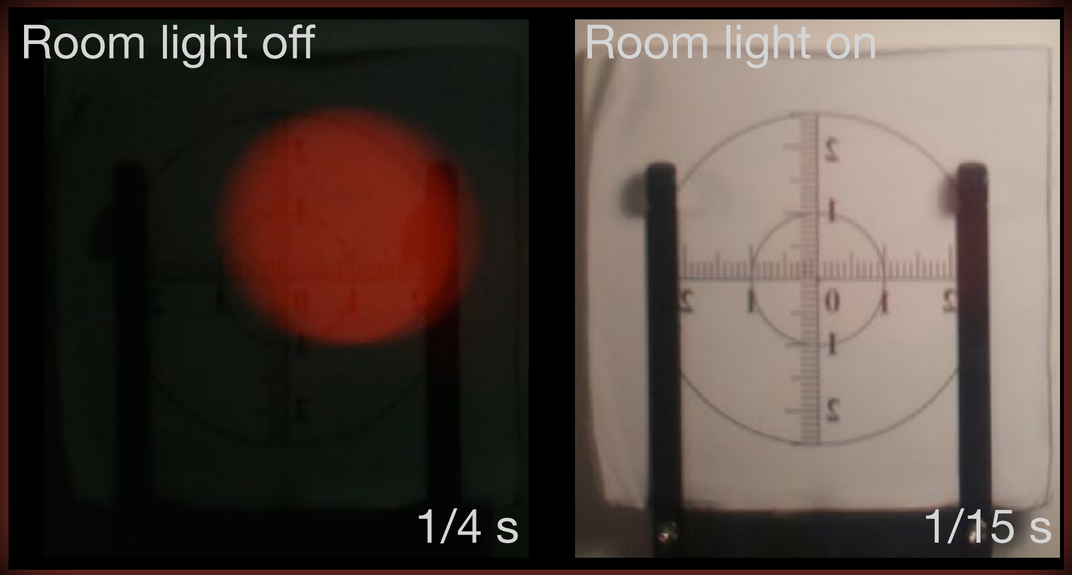
[WP25M-VIS, Thorlabs]

Implementation: Optical Setup



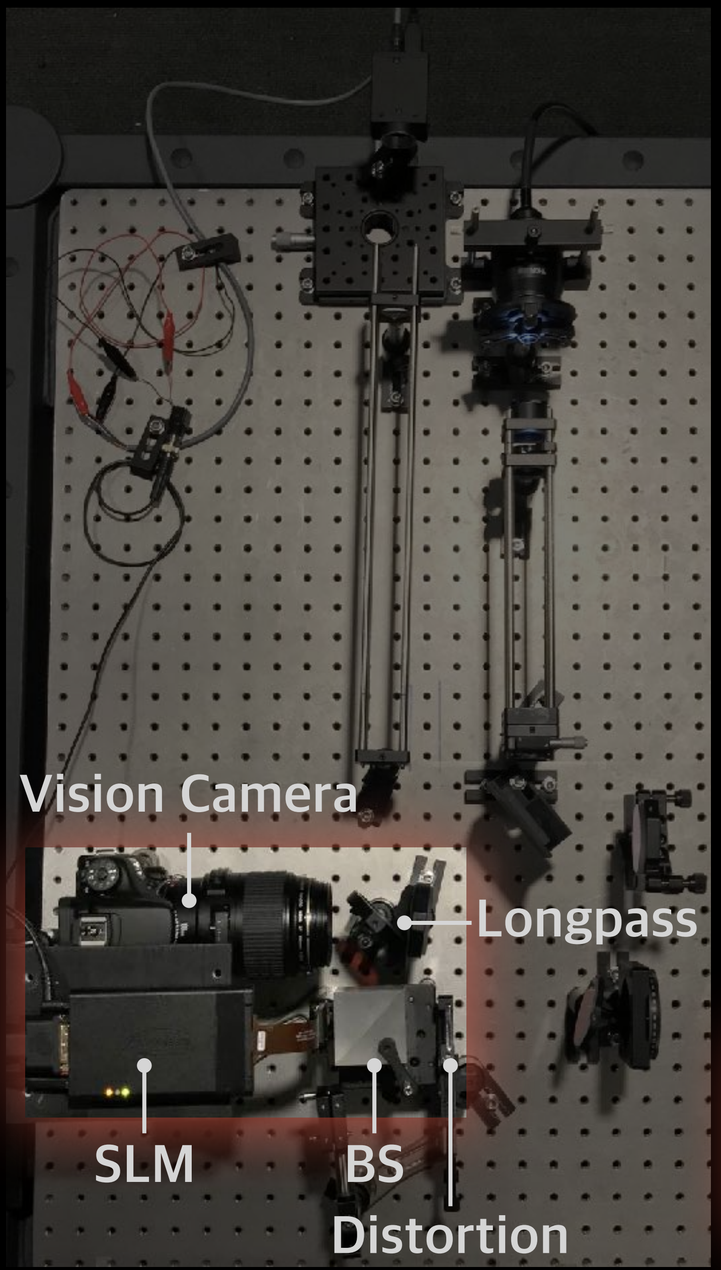
Make it invisible to the vision camera

650 nm Longpass



700 nm Longpass

Implementation: Optical Setup



Correction Component & Vision Camera

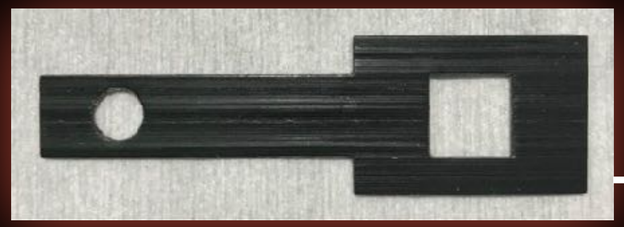
Vision Camera

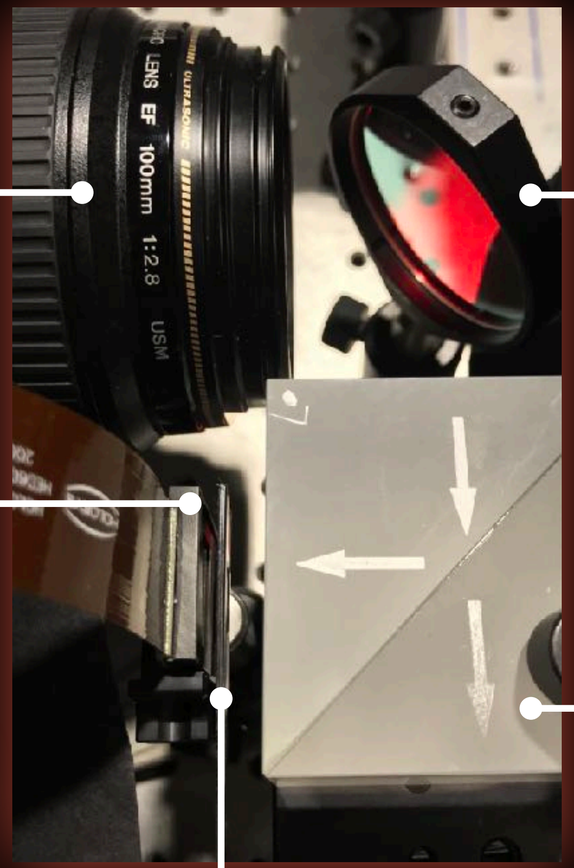
[EOS 70D, Canon]

SLM

[PLUTO-2-VIS-014-C, Holoeye]

[3D printed] Iris





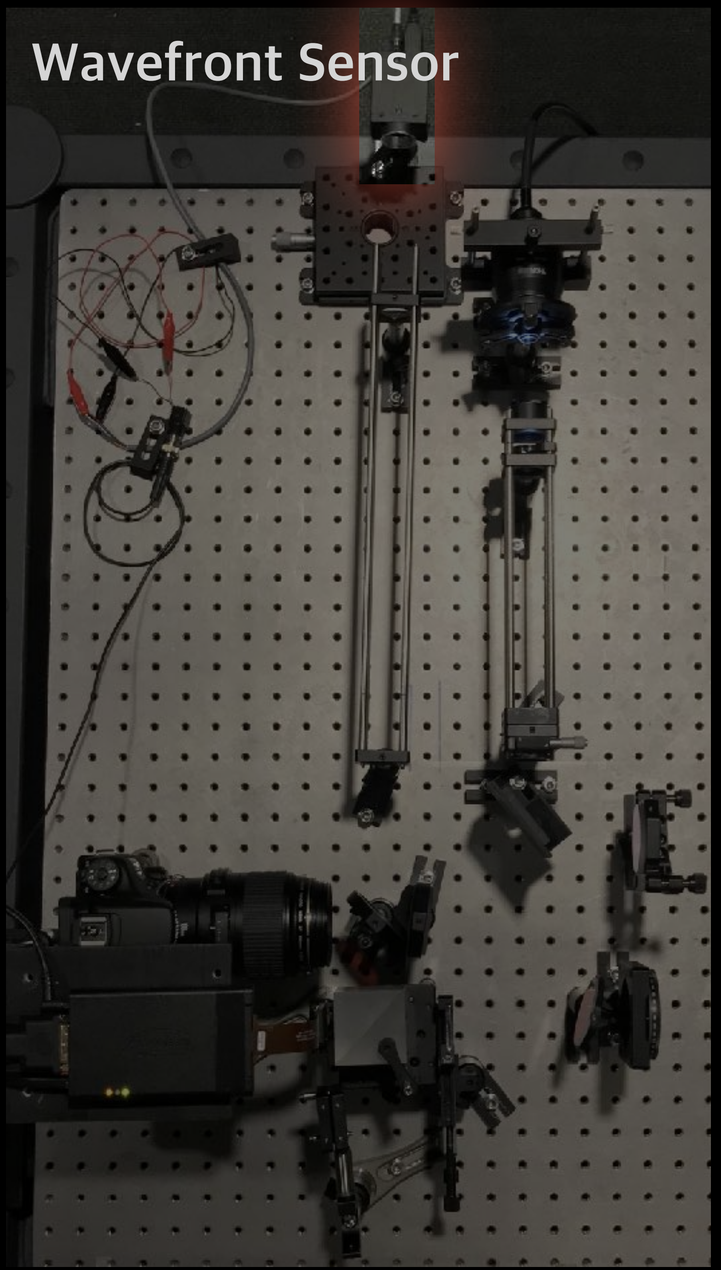
Longpass Dichroic

[DMSP650L, Thorlabs]

Beamsplitter

[BS031, Thorlabs]

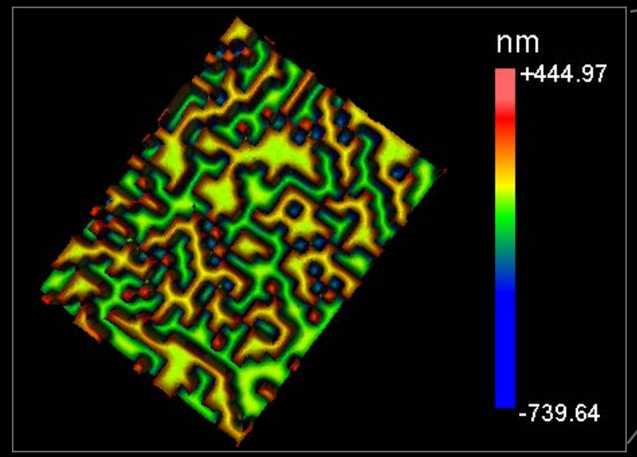
Implementation: Optical Setup



Wavefront Sensor Assembly

Statistics:

- 6.45 µm sensor pixel
- 12.9 µm mask pixel
- ~1.5 mm mask-sensor distance

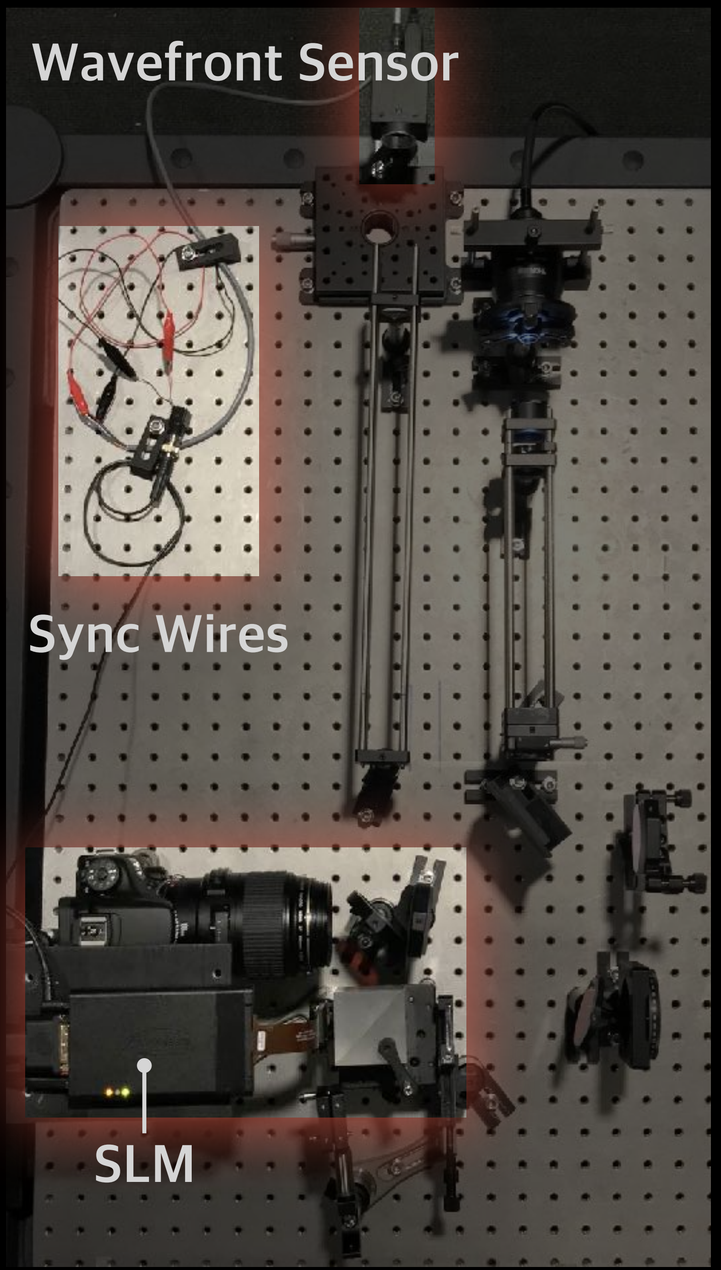


[Self-Fabricated]

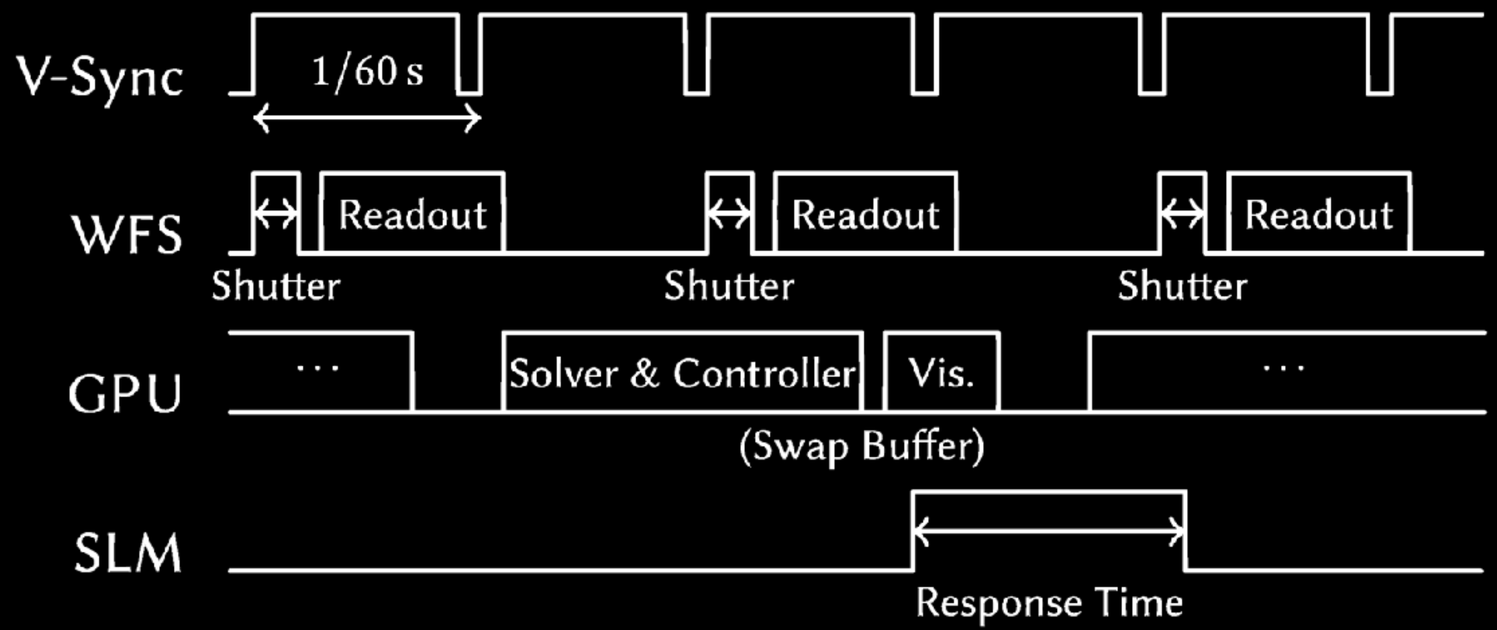
[ICX 285, Sony]

[GS3-U3-15S5M-C, PointGrey]

Implementation: Optical Setup



AO Sync and Timing Arrangement

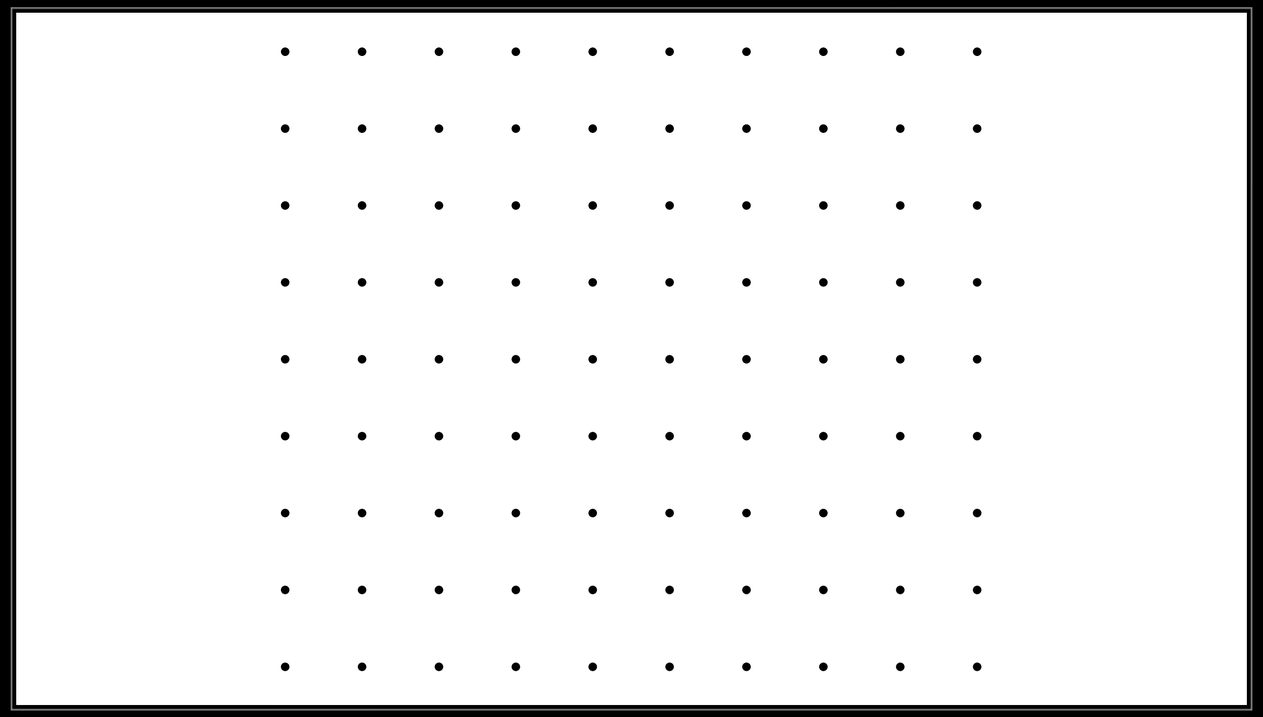


Performance:

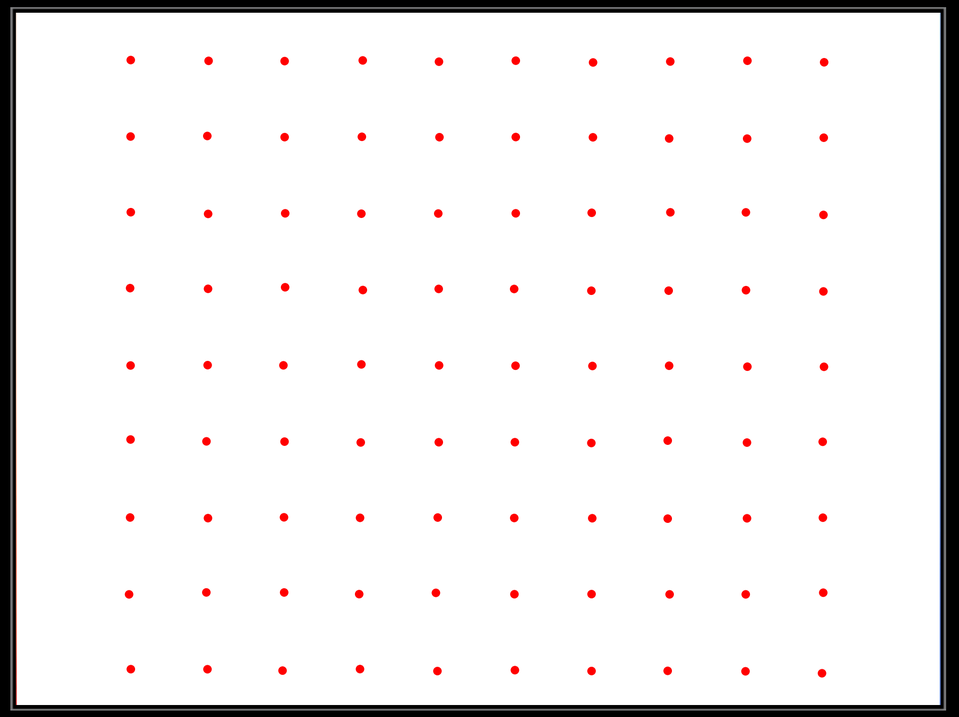
- 25~30 Hz sensing
- 10~12 Hz correction

Implementation: Calibration & Denoising

Calibration: Sensor & Corrector Alignment



SLM



Wavefront Sensor

Experimental Results

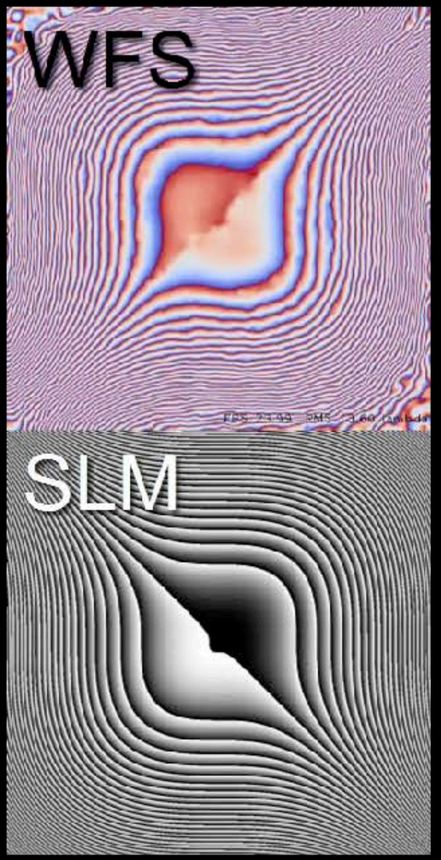
Result 1: PSF Tests

PSF test: cubic phase

hold

camera

reference



Result 1: PSF Tests

PSF test: microlens array

hold

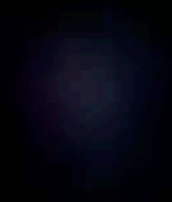
camera

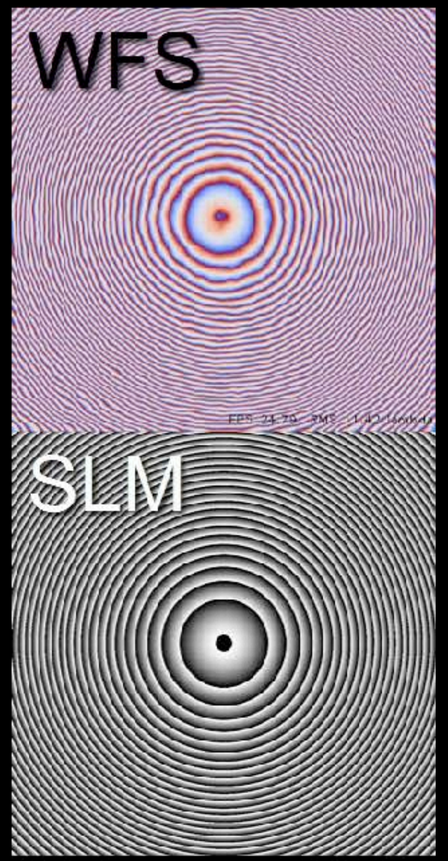
reference

Result 1: PSF Tests

PSF test: Zernike Z_4^0 (primary spherical)

hold





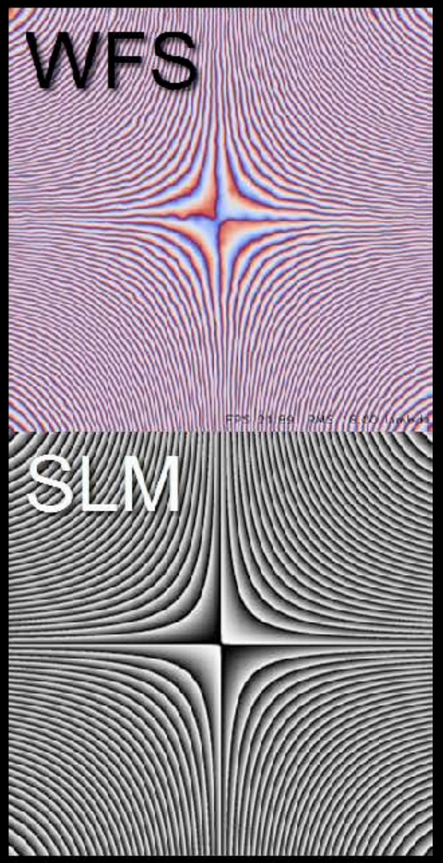
camera

reference

Result 1: PSF Tests

PSF test: Zernike Z_4^{-2} (secondary astigmatism)

hold



camera

reference

Result 1: PSF Tests

Static phase: lens f = -1000mm

AO off

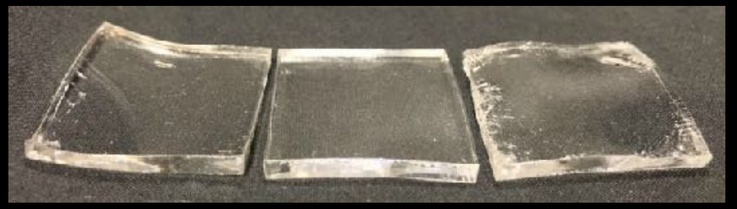
SLM

camera

reference

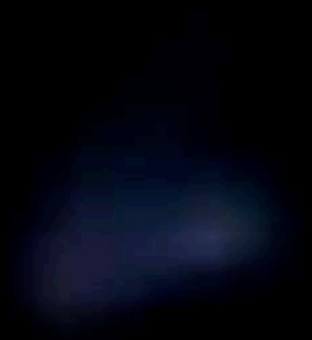
Result 1: PSF Tests

Static phase: warped plate 1



AO off

SLM

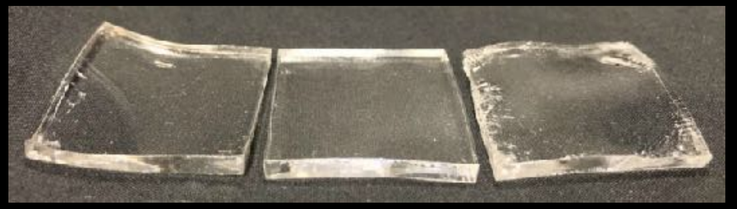


camera

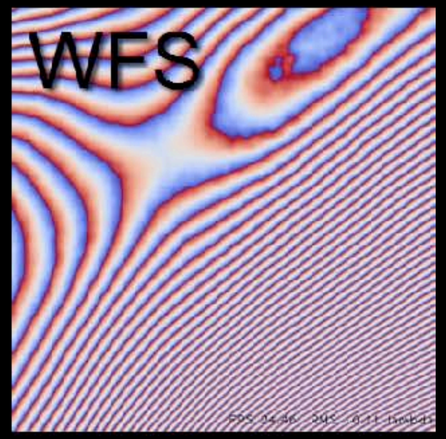
reference

Result 1: PSF Tests

Static phase: warped plate 2



AO off



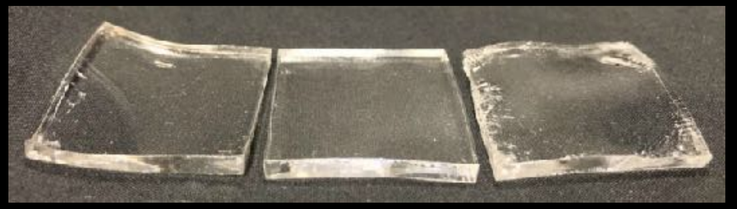
SLM

camera

reference

Result 1: PSF Tests

Static phase: warped plate 3



AO off

SLM

camera

reference

Result 2: Comparison with Existing Methods

Original (AO off)

Blind Deconvolution

[Krishnan et al. 2011]

[Sun et al. 2013]

Ours (AO on)

Non-Blind Deconvolution

[Levin et al. 2007]

[Cho et al. 2011]

Result 2: Comparison with Existing Methods

Original (AO off)

Blind Deconvolution

[Xu et al. 2013]

[Michaeli and Irani 2014]

Ours (AO on)

Non-Blind Deconvolution

[Ji and Wang 2012]

[Hu et al. 2014]

Result 2: Comparison with Software-Only Methods

Original (AO off)

Blind Deconvolution

[Pan et al. 2016]

Ringing artifacts:

- ill-condition PSF
- inaccurate PSF estimation

Ours (AO on)

Non-Blind Deconvolution

[Dong et al. 2017]

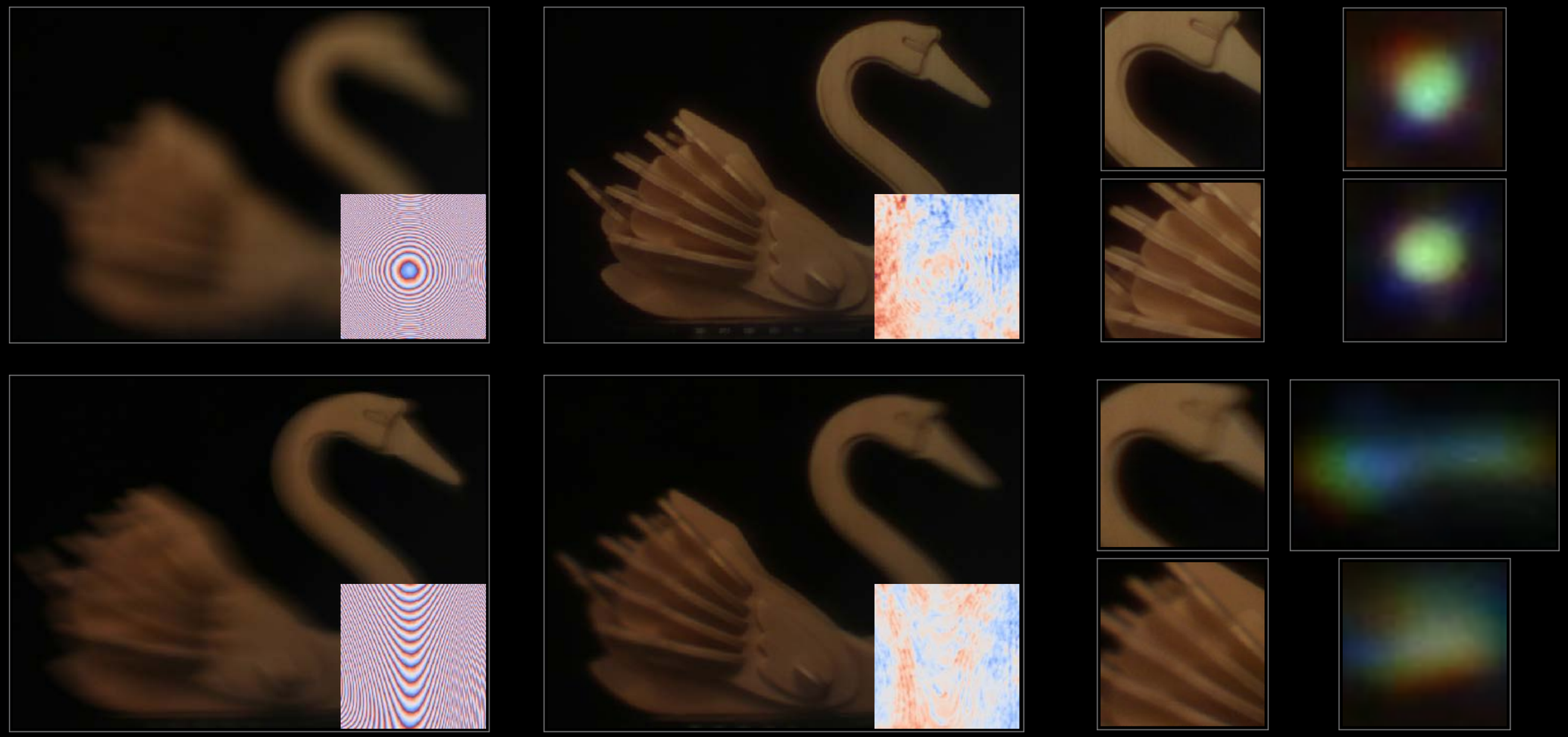
Result 3: Dynamic Deblurring

Dynamic phase： yellow car (speed 3x)

AO off

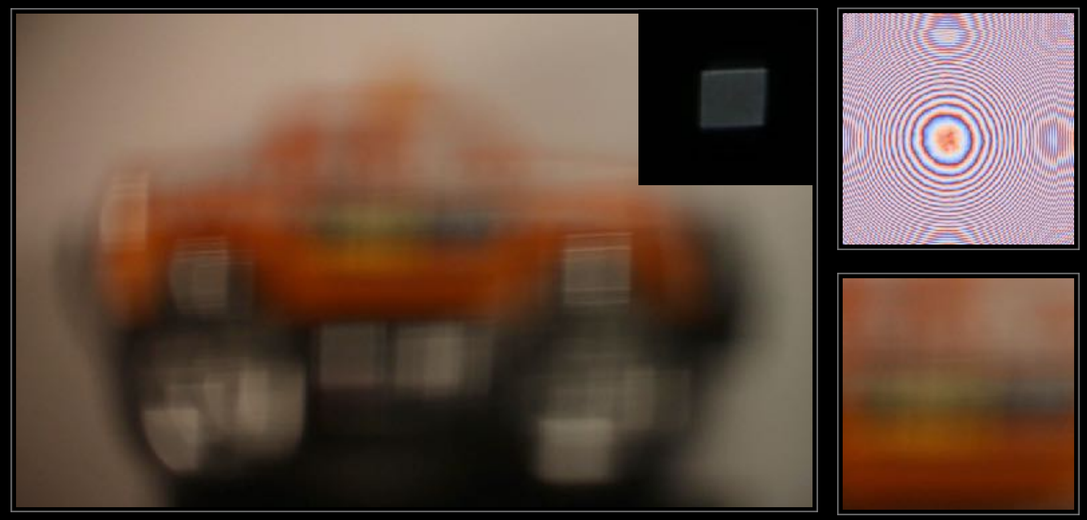
AO on

Limitations: Nonuniform PSF (Anisoplanatism)



Summary

- First AO system for photography and machine vision
- High resolution wavefront sensing
- Large-scale phase distortion correction



AO Off

AO On

Thank You !

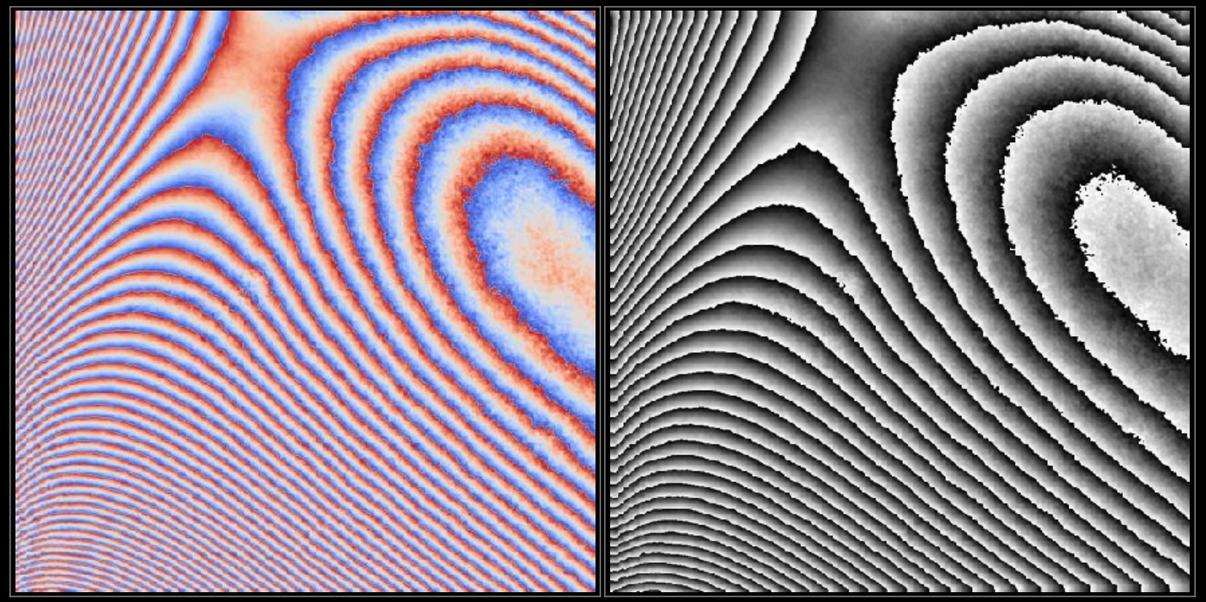
This work was supported by King Abdullah University of Science and Technology under Individual Baseline Funding.

https://github.com/vccimaging/MegapixelAO


KAUST

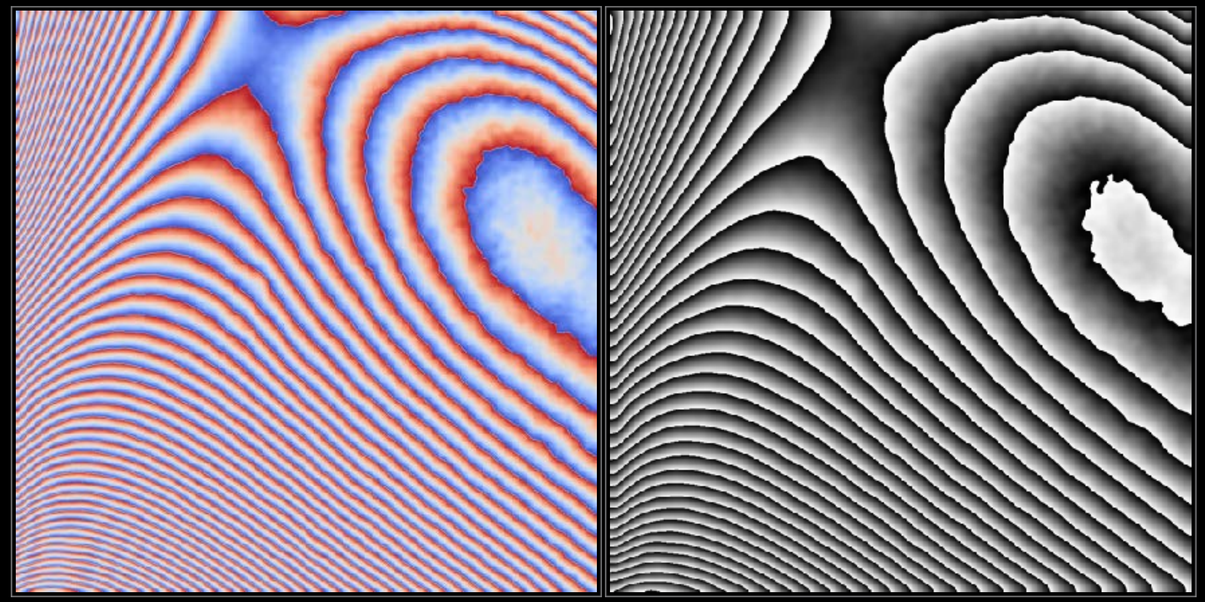
Implementation: Denoising

Original

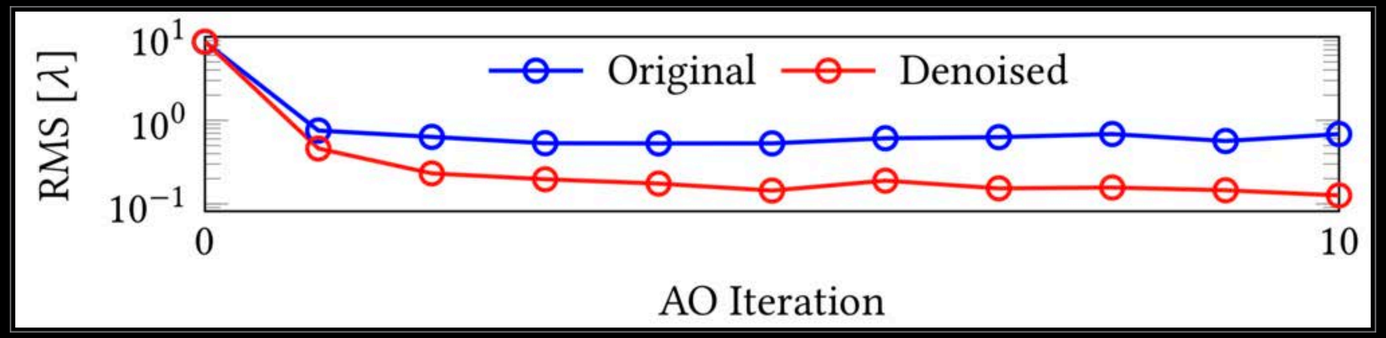


Wavefront Sensor SLM

Bilateral Filtered



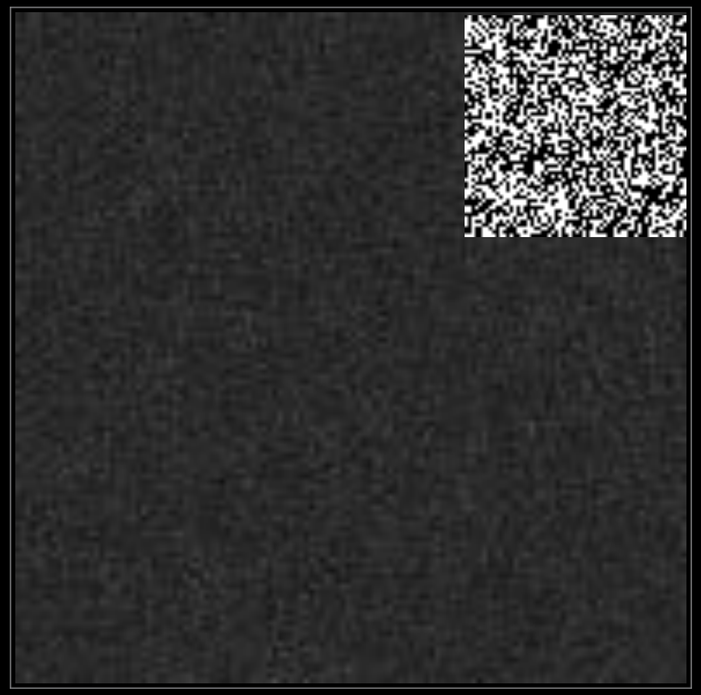
Wavefront Sensor SLM



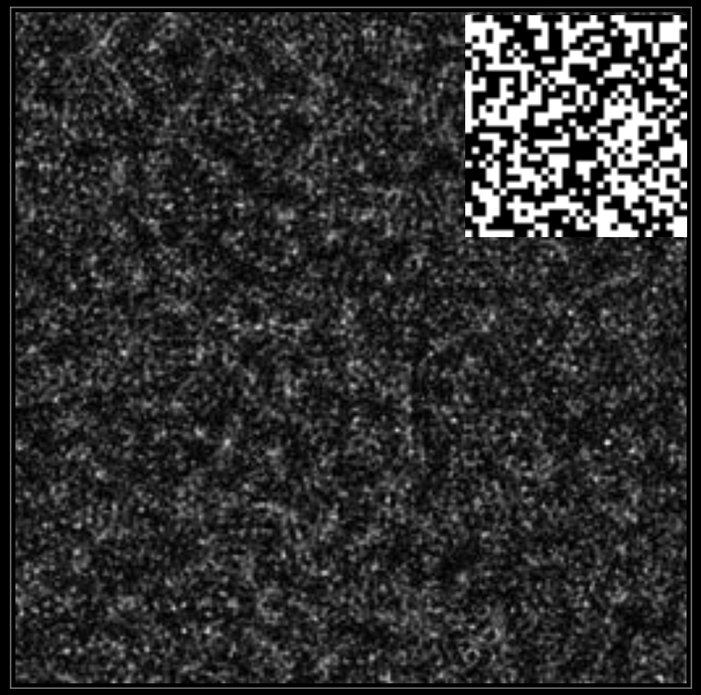
Coded Wavefront Sensor: What are Good Patterns?

Images under amplitude mask (simulated)

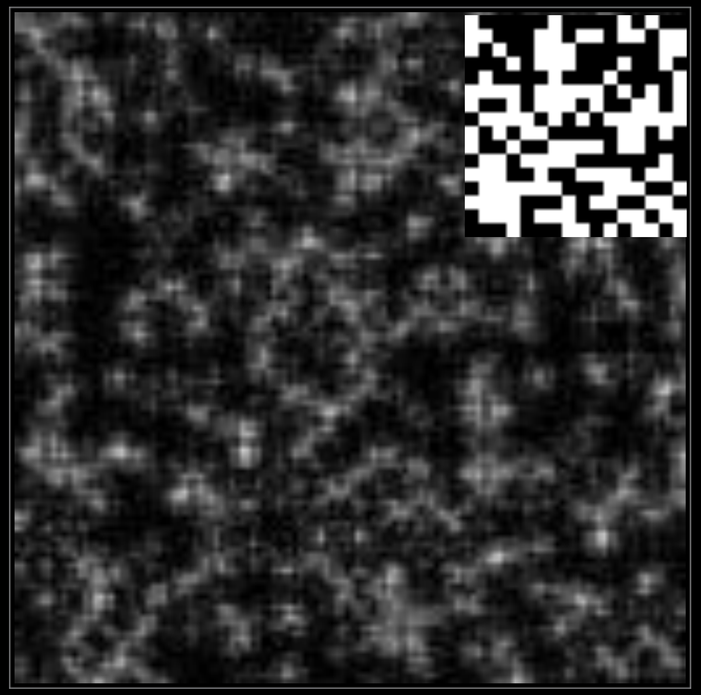
Mask pixel size matters



(Too uniform)



Good

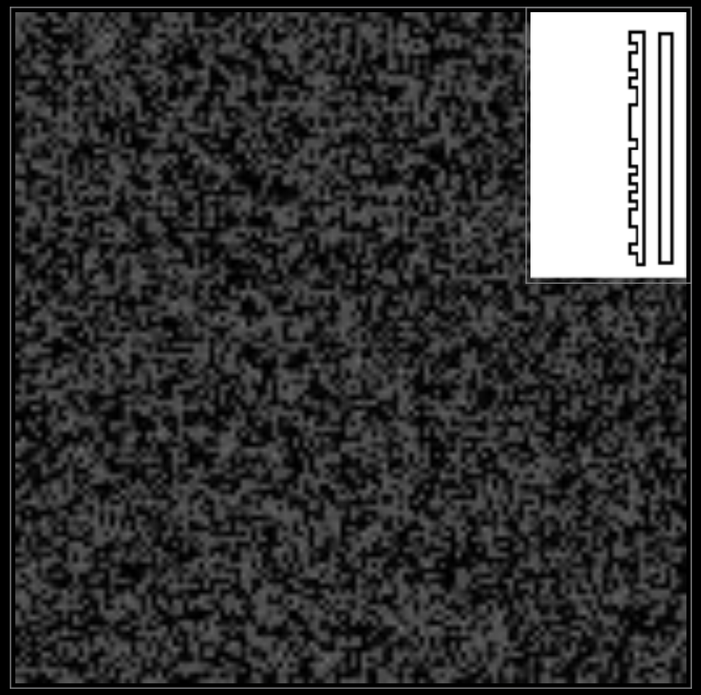


(Too sparse)

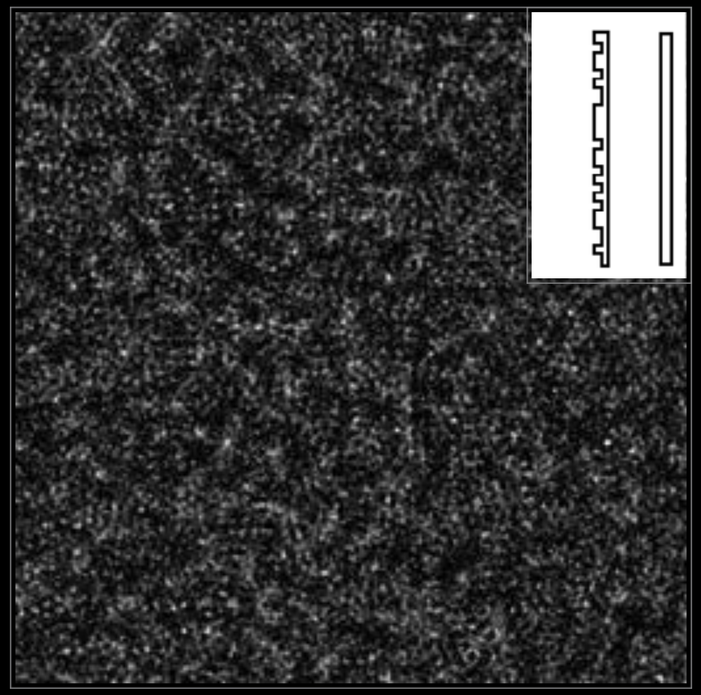
Coded Wavefront Sensor: What are Good Patterns?

Images under amplitude mask (simulated)

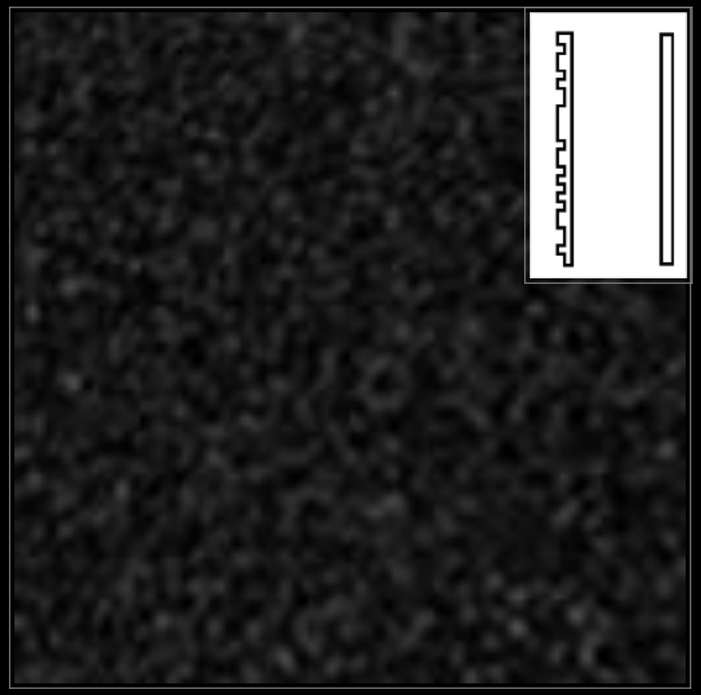
Distance matters



(Too edgy)



Good

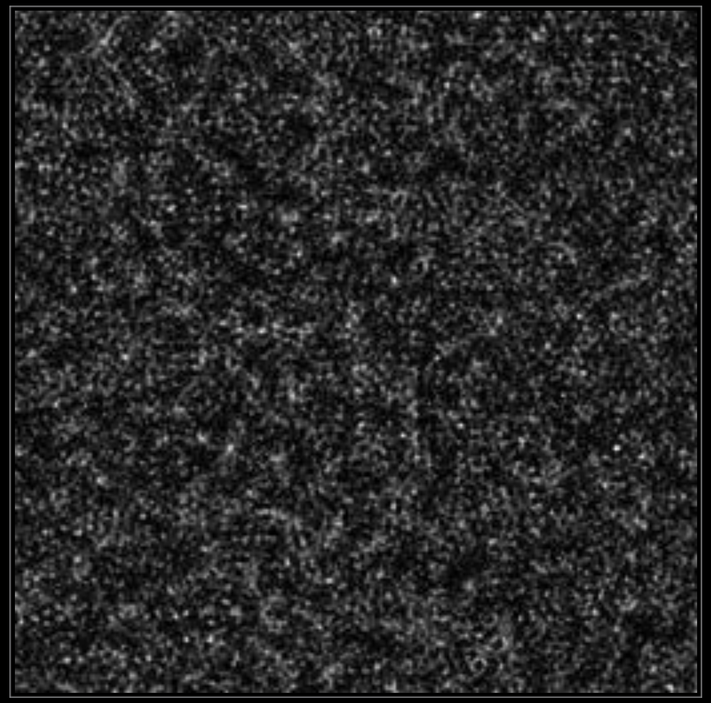


(Too blur)

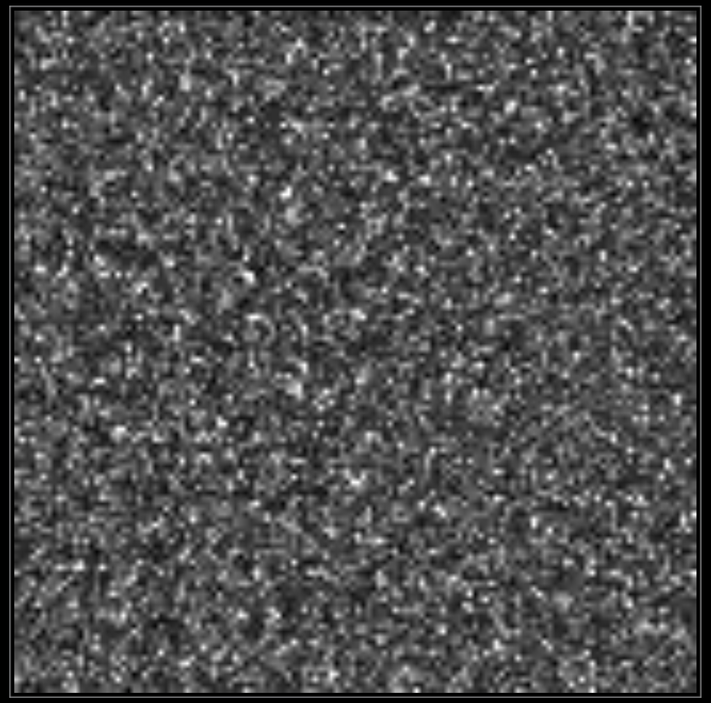
Coded Wavefront Sensor: What are Good Patterns?

Images under amplitude & **phase** mask (simulated)

Better contrast & Light efficiency



Amplitude mask

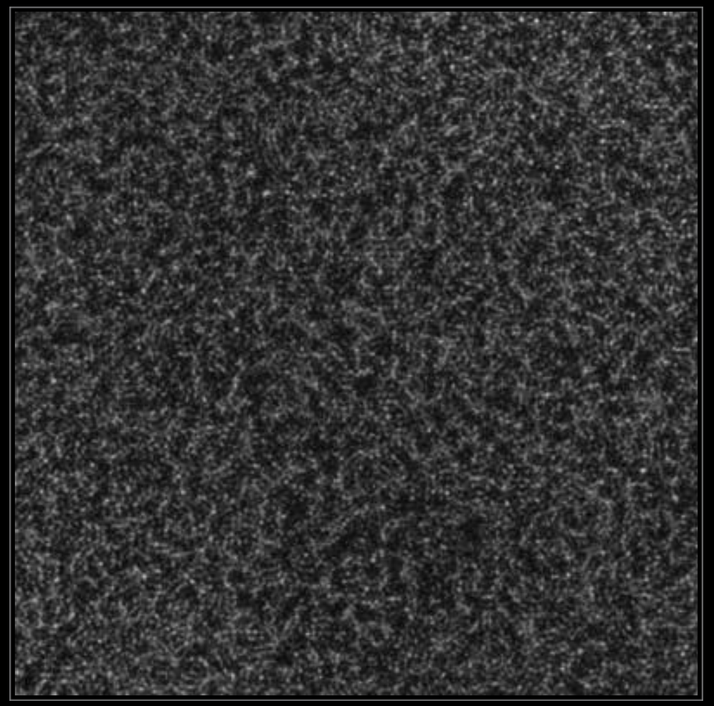


Phase mask

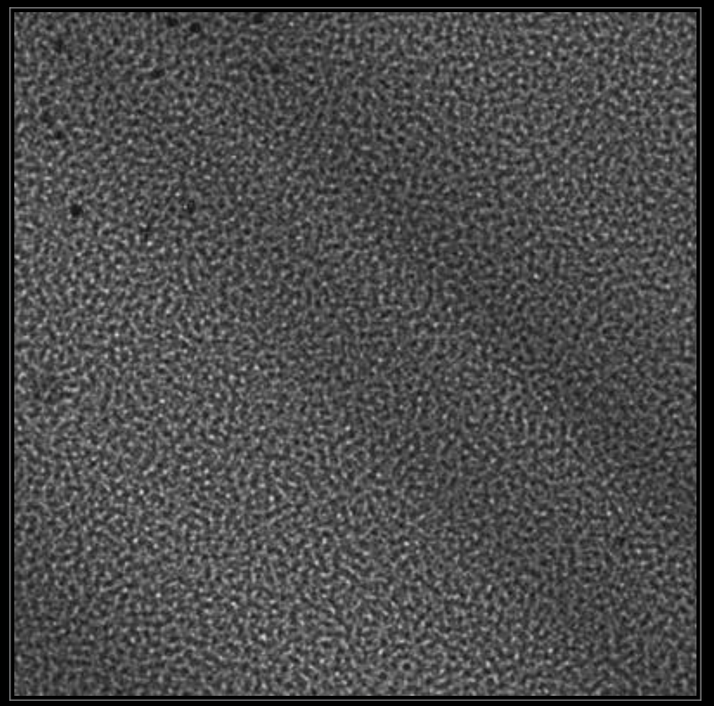
Coded Wavefront Sensor: What are Good Patterns?

Images under amplitude & **phase** mask (lab data)

Better contrast & Light efficiency



Amplitude mask



Phase mask

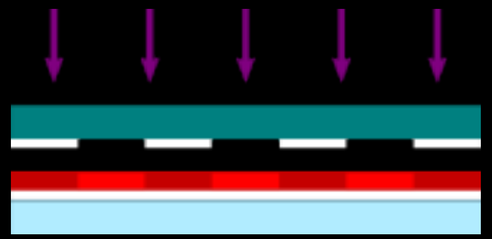
Implementation: Mask Fabrication

Soda Lime Photomask

Cr on Fused Silica Wafer

Photoresist

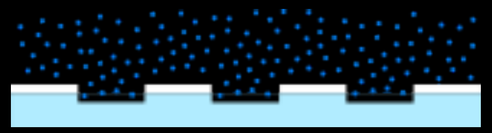
UV Light



Development

Cr Etching

Plasma (Ar + SF_6)



Binary Phase Mask