Compact Snapshot Hyperspectral Imaging with Diffracted Rotation

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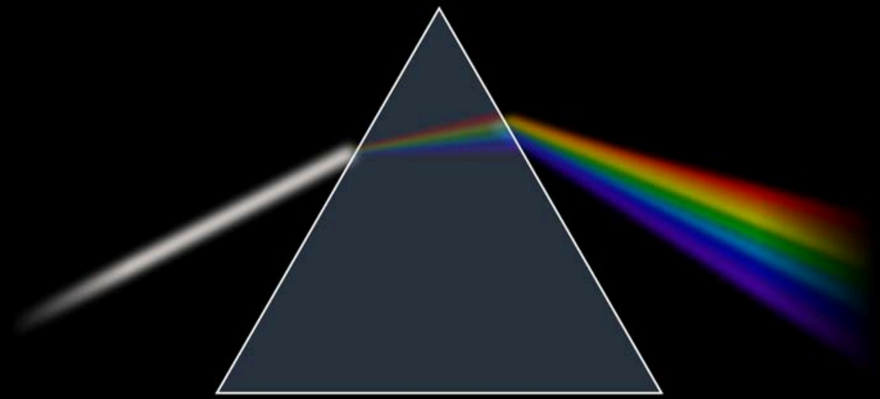
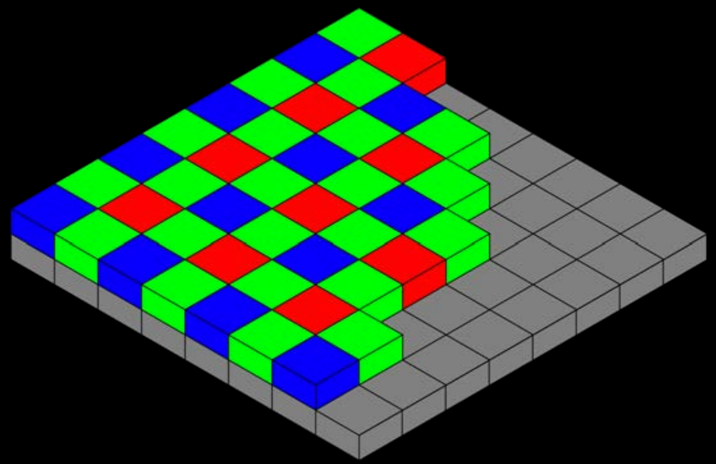
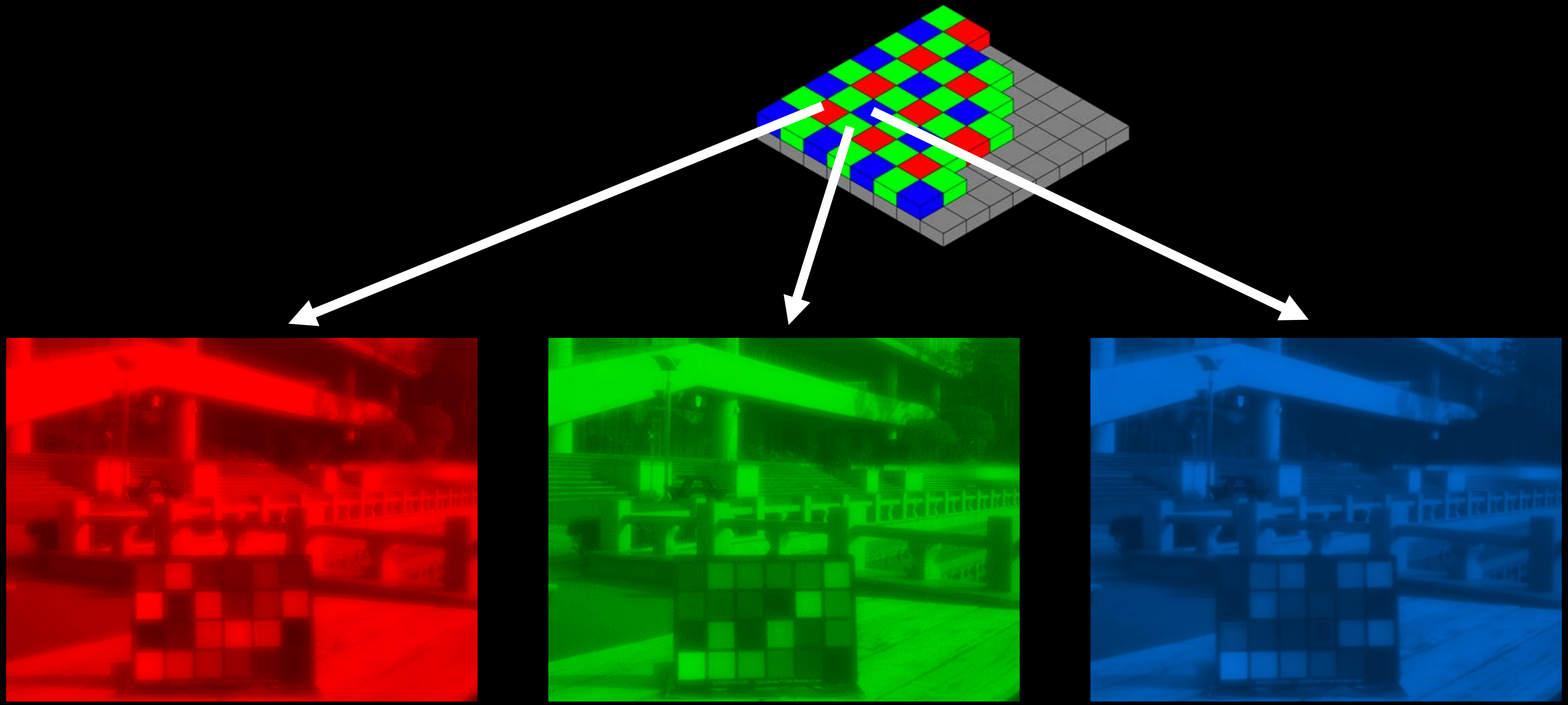
Light and Color Imaging


Continuous spectra of light


Bayer pattern

Conventional RGB Camera

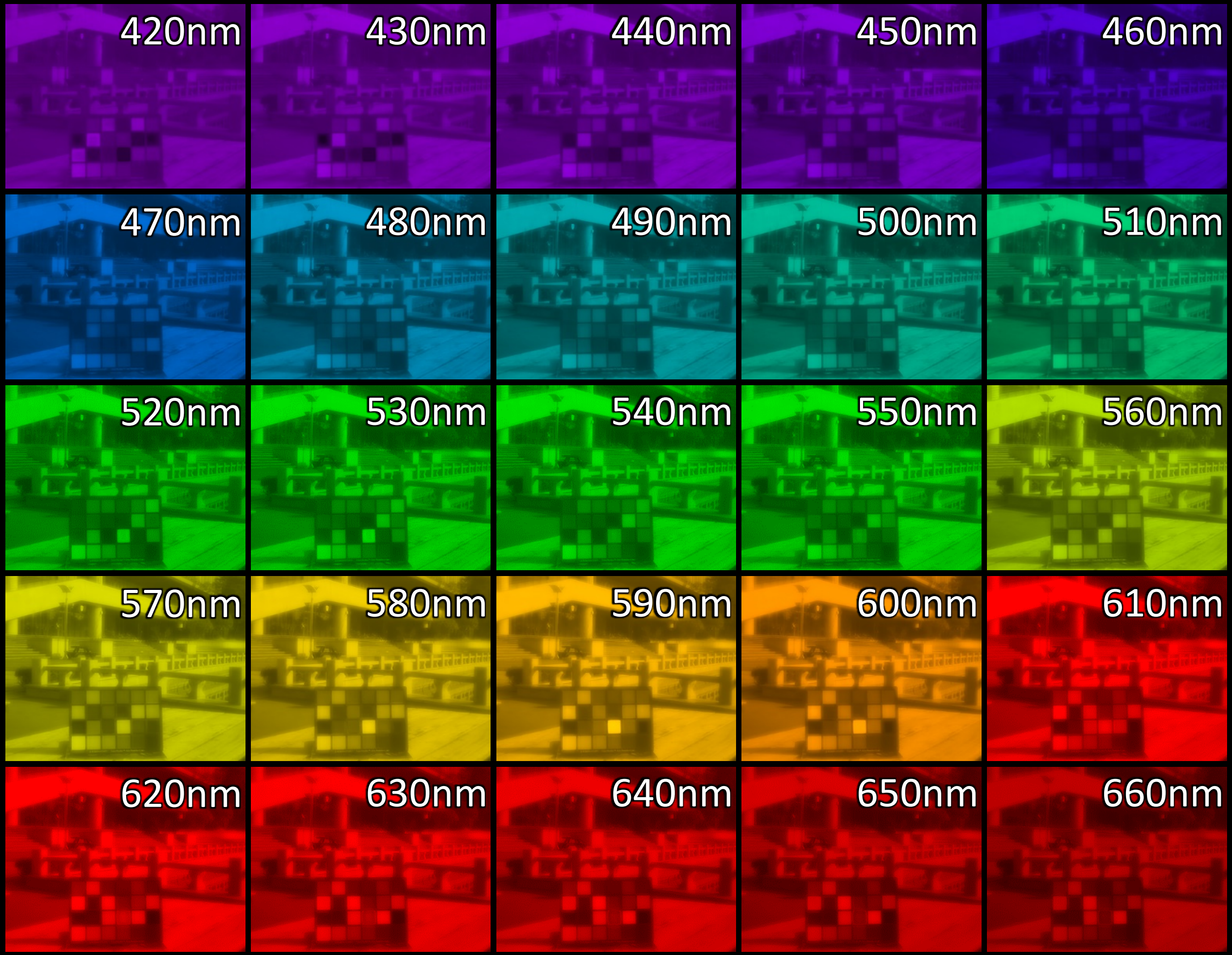


Red

Green

Blue

Hyperspectral Imaging



Wavelength: 420nm – 660nm

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Goal

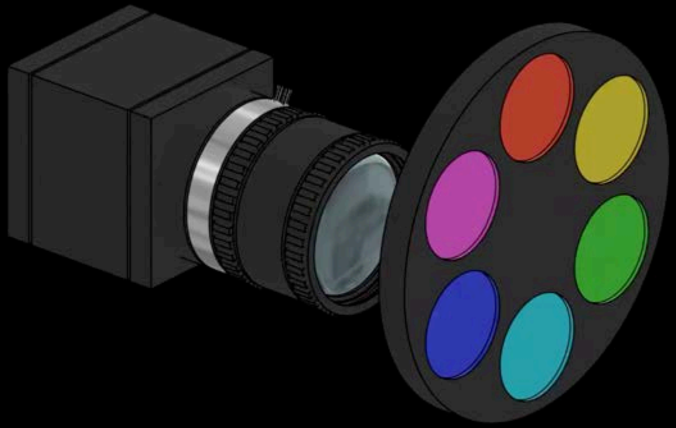
Single RGB input

Our algorithm

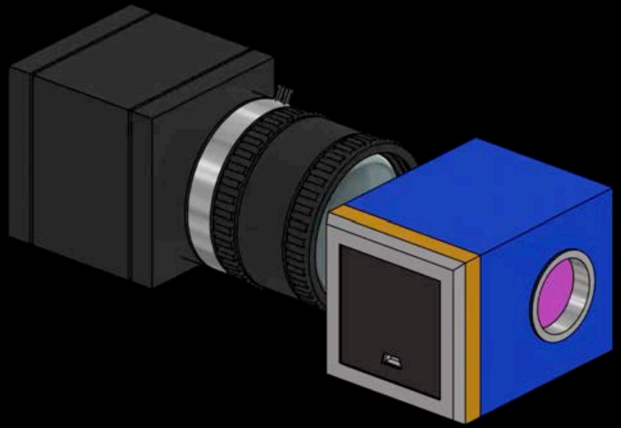
Hyperspectral image

Related Work: Multi-shot Hyperspectral Imaging

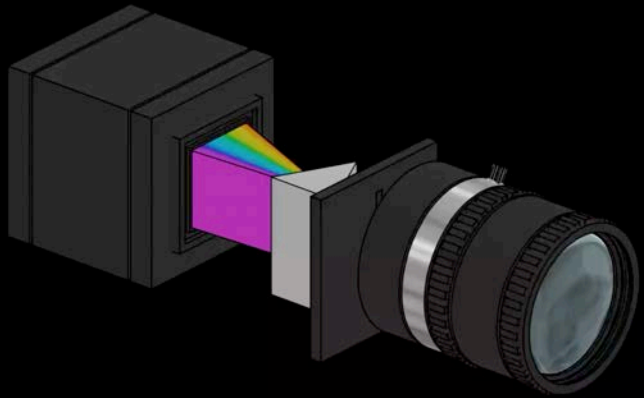
- Traditional hyperspectral camera requires multiple captures



Bandpass filter



LCTF (liquid crystal tunable filter)



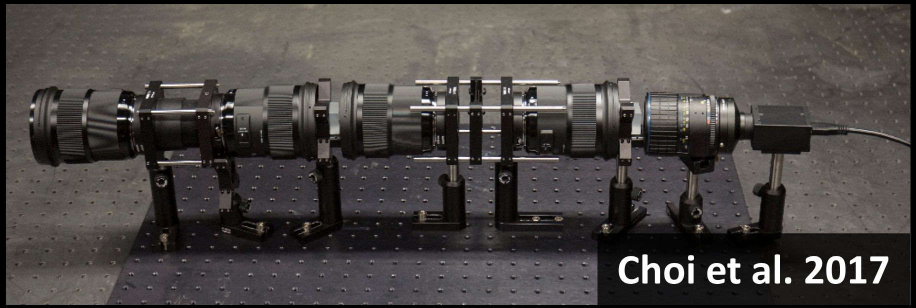
Pushbroom
(line scanning)

Unable to capture dynamic scenes

Related Work: Single-shot Hyperspectral Imaging

- Recently, single-shot hyperspectral cameras have been introduced

Computed Tomography Imaging Spectroscopy (CTIS)



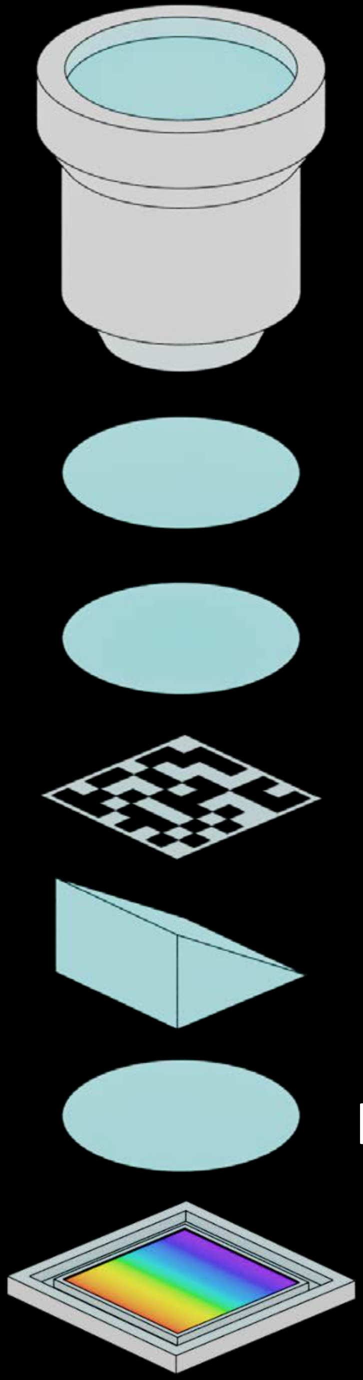
Compressive Coded Aperture Spectral Imaging (CASSI)

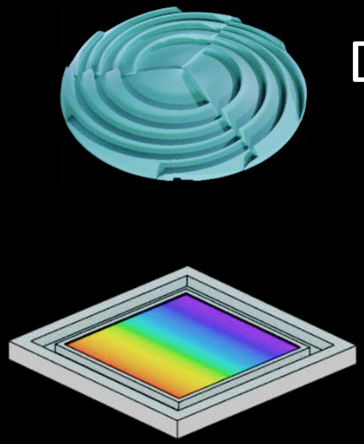
Prism-Mask Multispectral Video Imaging System (PMVIS)

Too large form factor

Goal

Snapshot hyperspectral imager

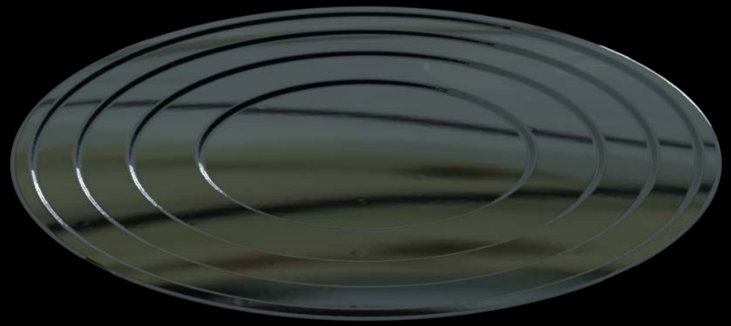




Diffractive Optical Element (DOE)

Convex lens

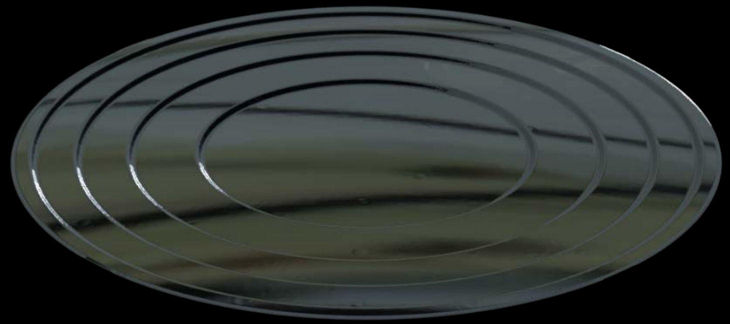
DOE



	Convex lens	DOE
Control light field	Refraction	Diffraction
Structure	Macro structure	Micro structure
Form factor	Thick	Flat
Design custom PSF	Limited	Various PSF designed

Fresnel Lens

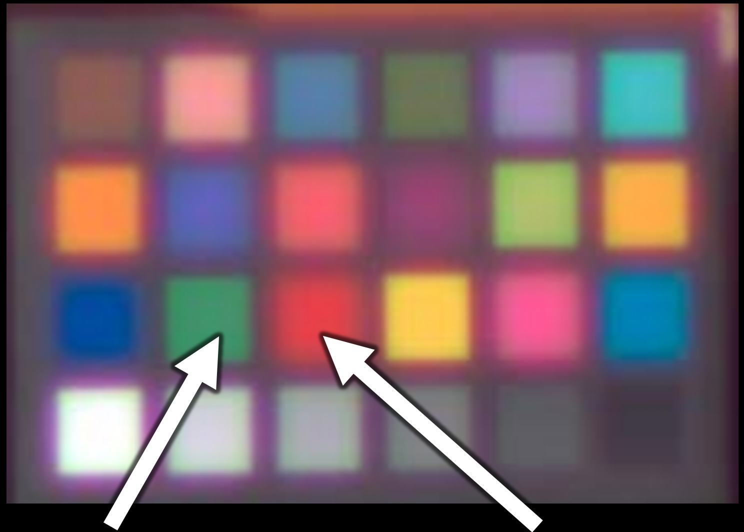
- Fresnel lens has been used commonly for various imaging applications



Limitation of Existing Fresnel Lens

Original scene

Captured by Fresnel lens



Focused

Defocused

Due to chromatic aberration

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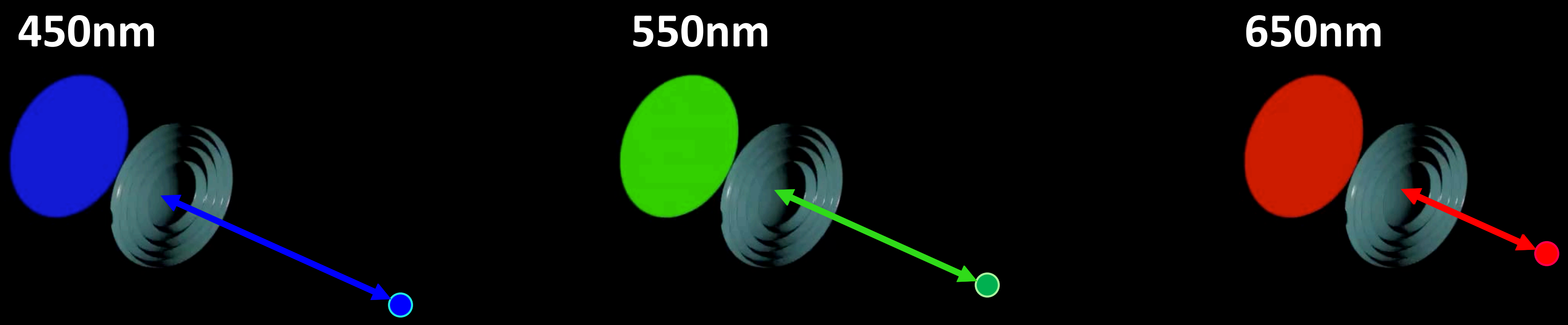
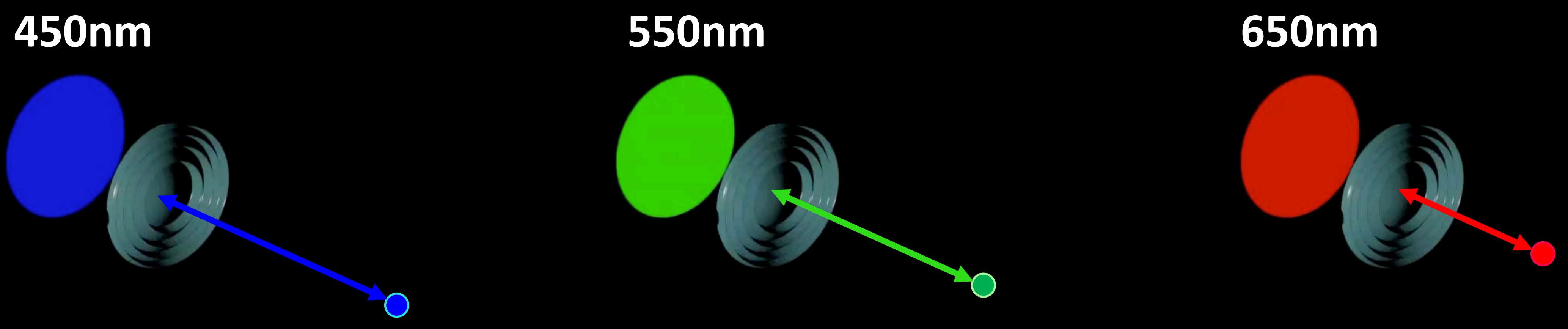
Fresnel Propagation with Different Wavelength



Fresnel Propagation with Different Wavelength

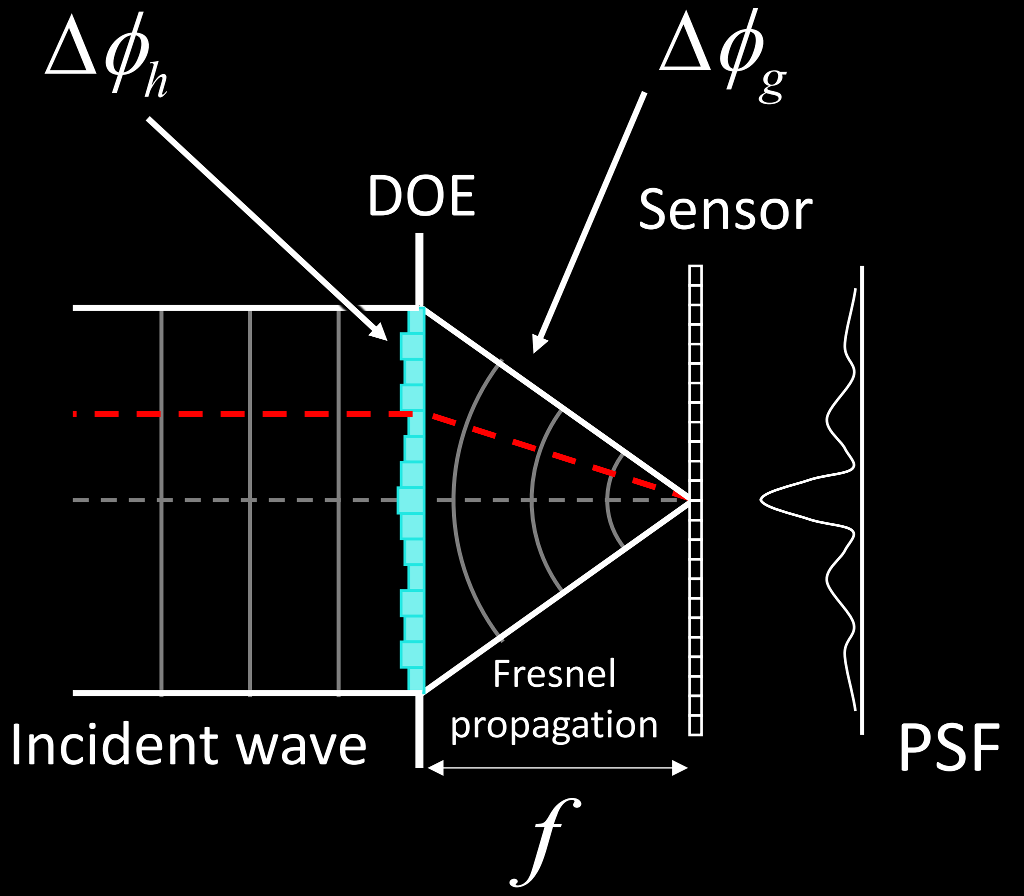


Focal length difference:

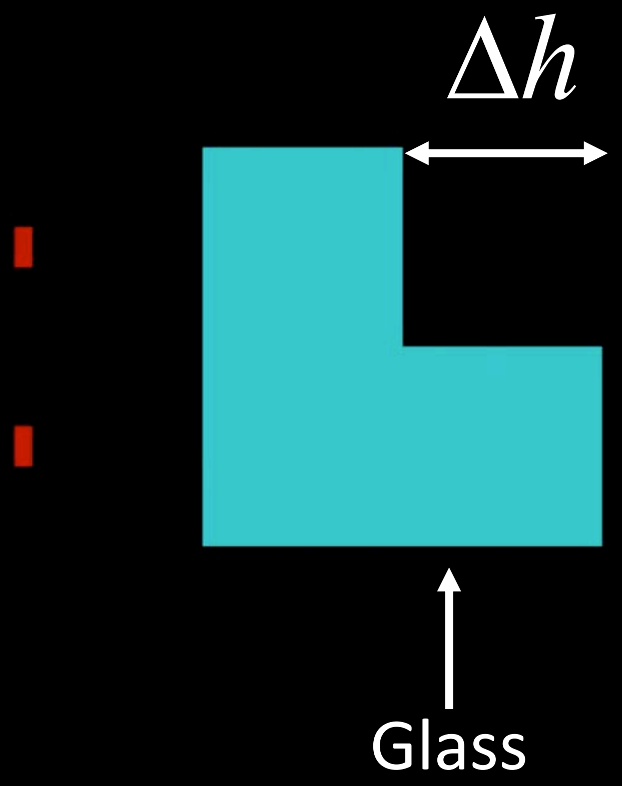
Blue > Green > Red

Our DOE: Phase Shift by

Medium + Propagation



Our DOE: Phase Shift by Medium $\Delta\phi_h$



Path difference

$$\Delta\phi_h = 2\pi \frac{\boxed{\Delta\eta_\lambda \Delta h}}{\lambda}$$

c : light speed

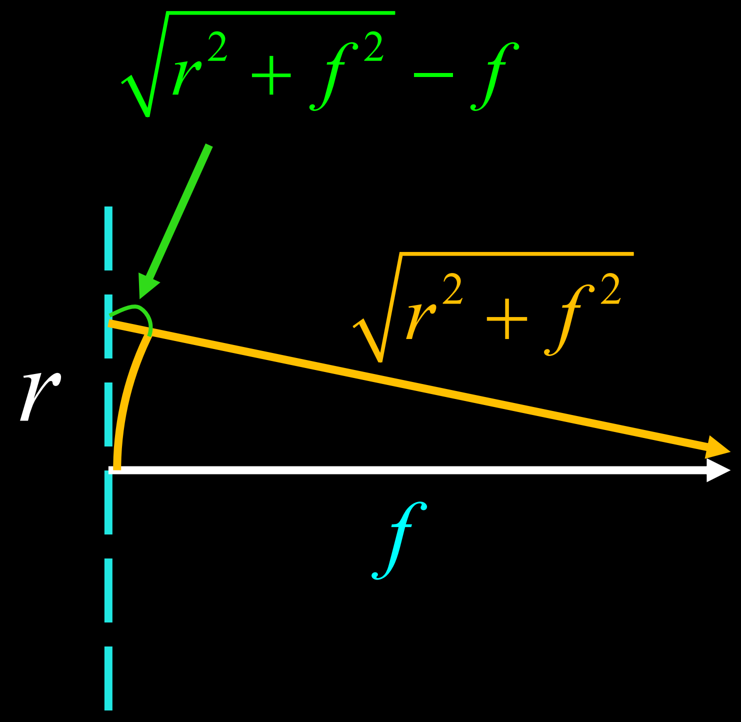
η : refractive index

$\Delta\eta_\lambda$: refractive index difference

Δh : height difference

$\Delta\phi_h$: phase shift by height

Our DOE: Phase Shift by Propagation $\Delta\phi_g$



Phase at radius *r*

Path difference

$$\Delta\phi_g = 2\pi \frac{\sqrt{r^2+f^2}-f}{\lambda}$$

λ : target wavelength

f : target focal length

Constructive Interference Condition

$$\Delta\phi_h + \Delta\phi_g = 2\pi n$$

where n is some integer

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Constructive Interference Condition

$$2\pi\frac{\Delta\eta_\lambda \boxed{\Delta h}}{\lambda} + 2\pi\frac{\sqrt{r^2+f^2}-f}{\lambda} = 2\pi n$$

where n is some integer

Height Equation

$$\Delta h = \frac{n\lambda - \left(\sqrt{r^2 + f^2} - f\right)}{\Delta\eta_\lambda}$$

where n is some integer $\quad -\frac{\lambda_{\max}}{\Delta\eta_{\lambda_{\max}}} \leq \Delta h \leq 0$

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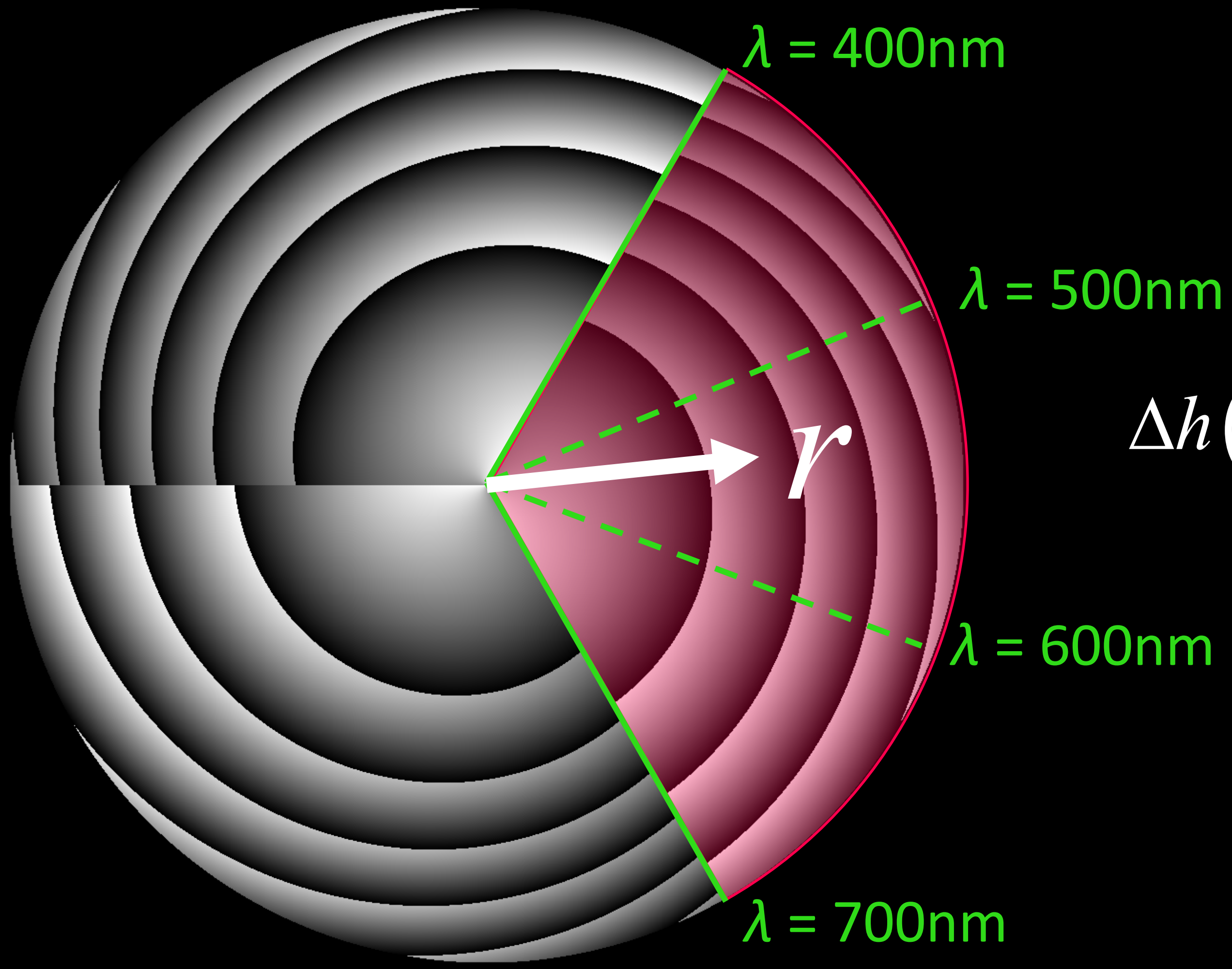
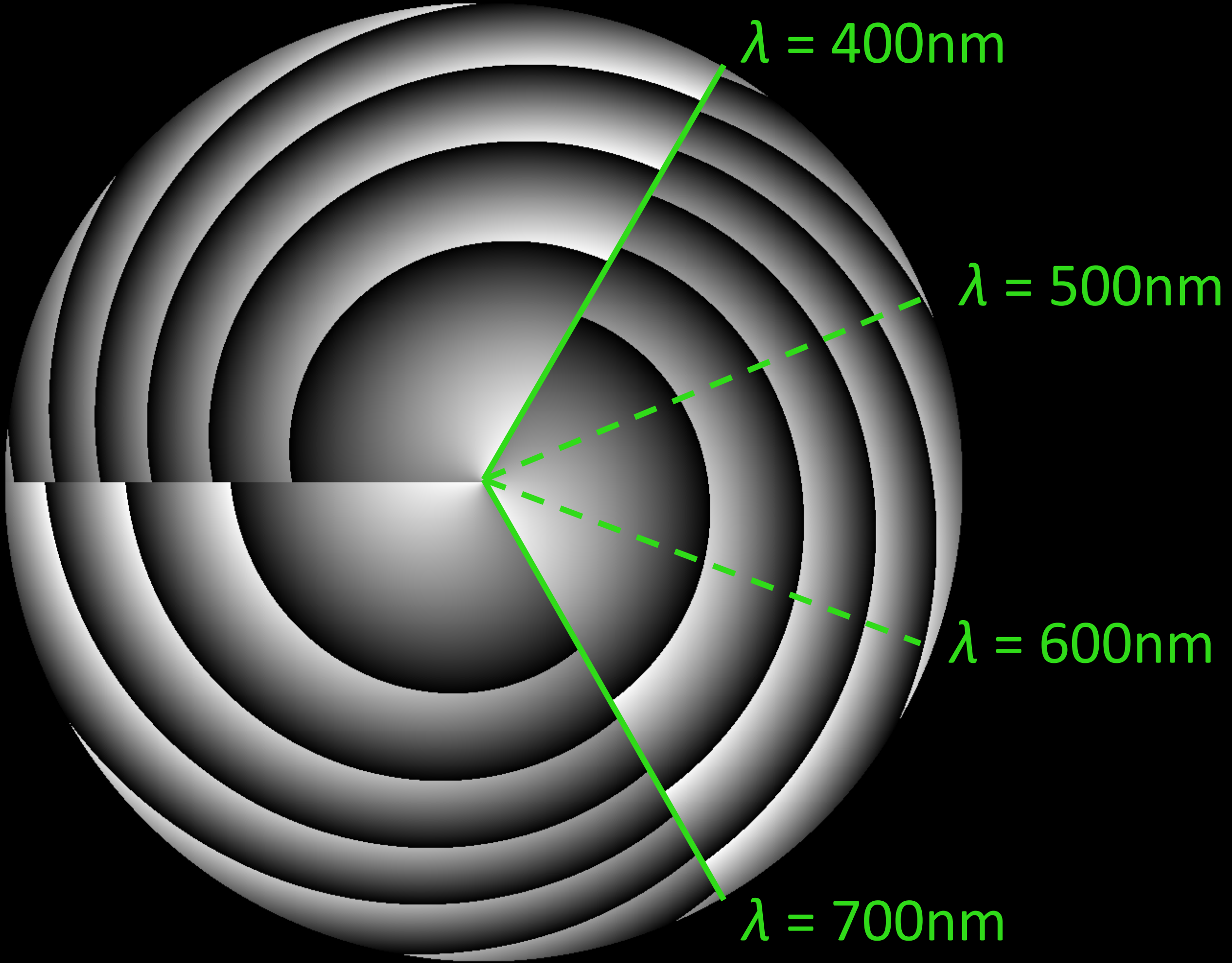
Our Design of the DOE Height Field

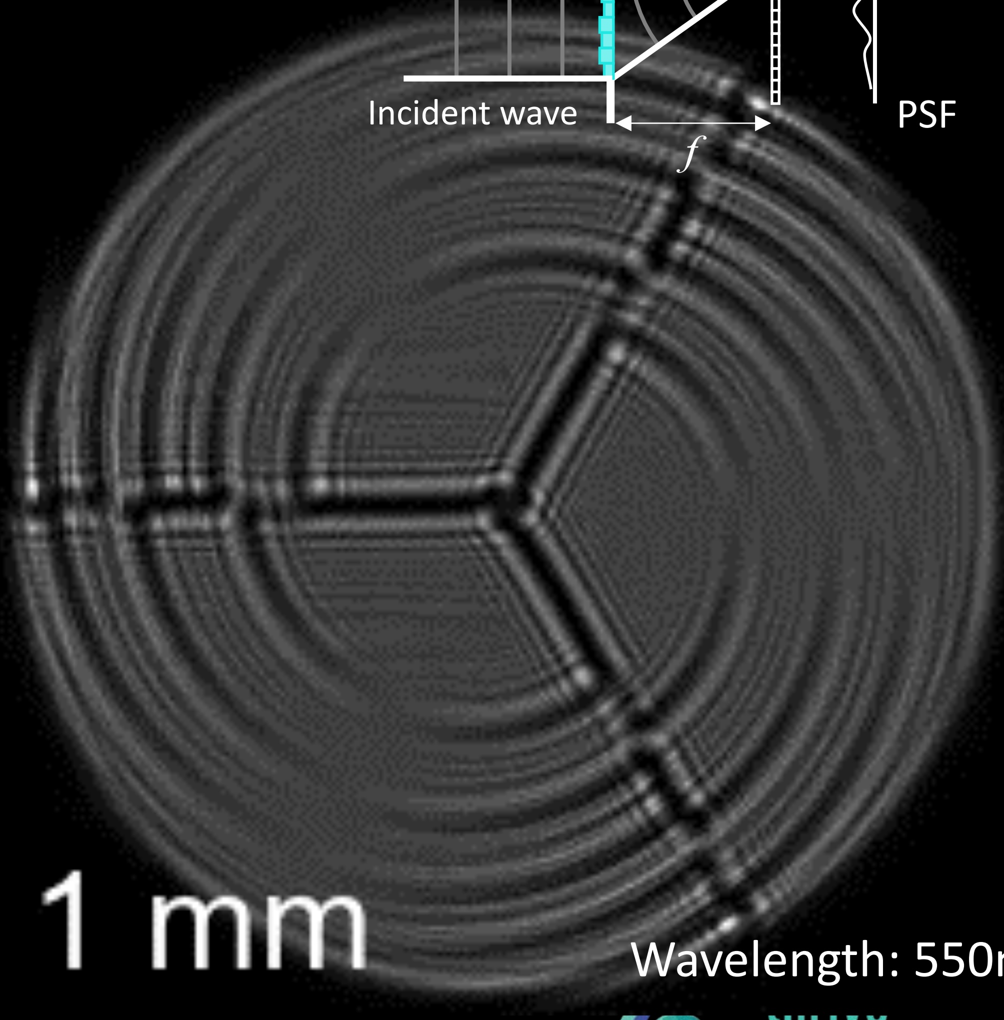


$$\Delta h\left(r, \lambda(\theta)\right) = \frac{n\lambda(\theta) - \left(\sqrt{r^2 + f^2} - f\right)}{\Delta \eta_\lambda}$$

where $0° \leq \theta < 120°$, f is fixed

Our DOE Light Propagation





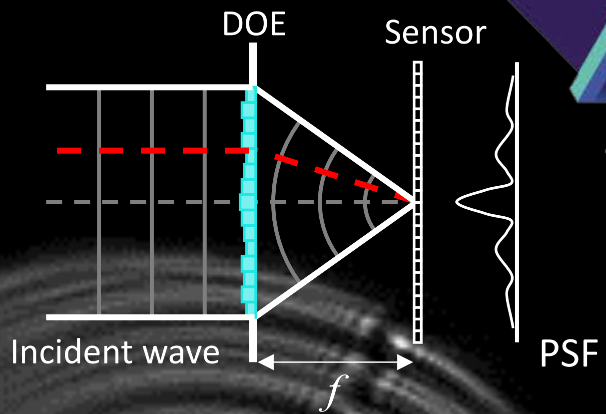
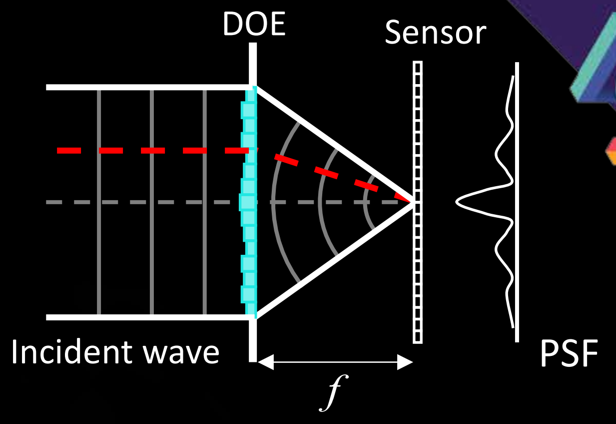
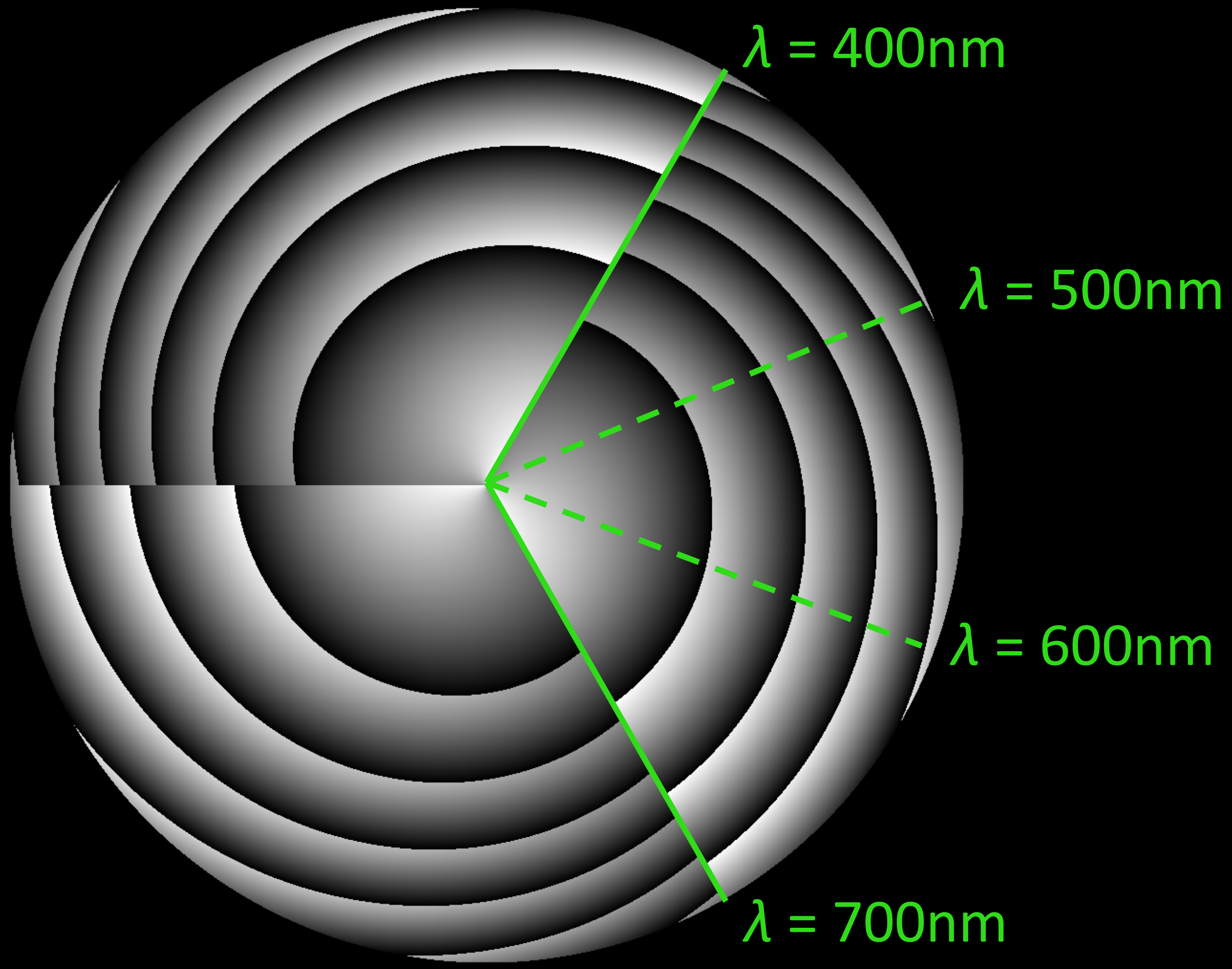


Image plane distance

Our DOE Point Spread Function





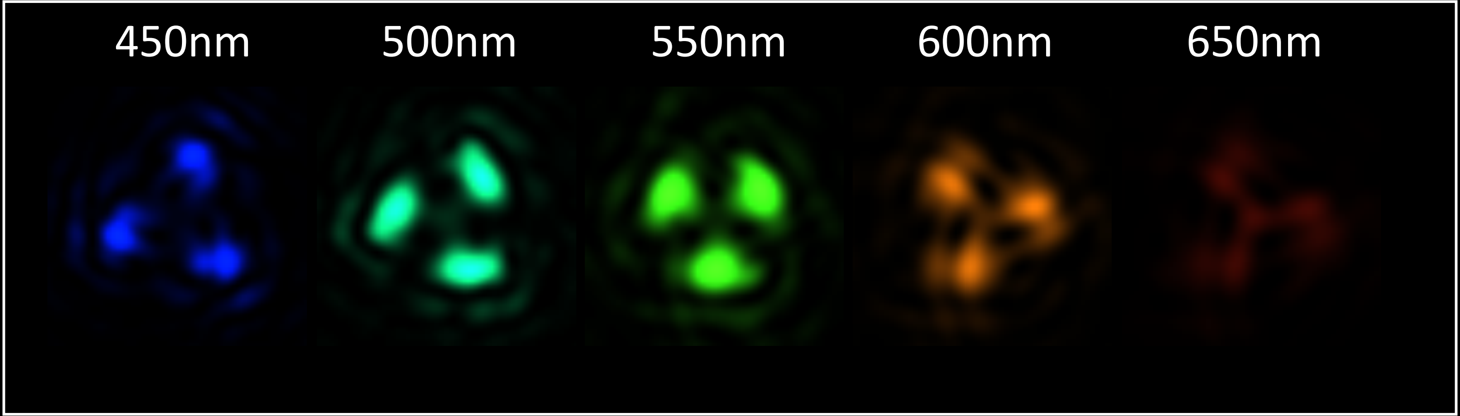
50 mm

Image plane distance

Wavelength: 550nm

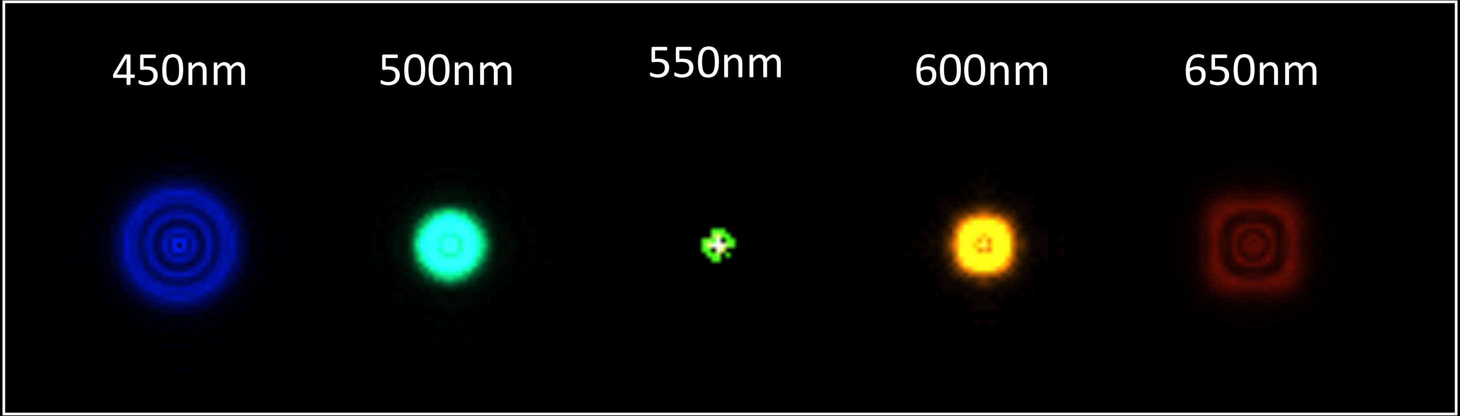
Our DOE: Spectrally-Varying PSF

Our DOE

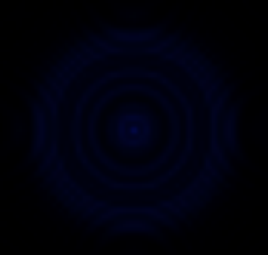


420nm

Fresnel DOE



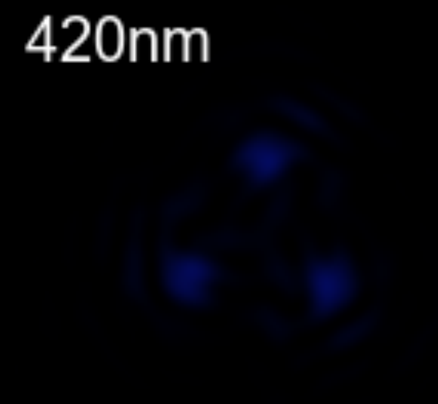
420nm



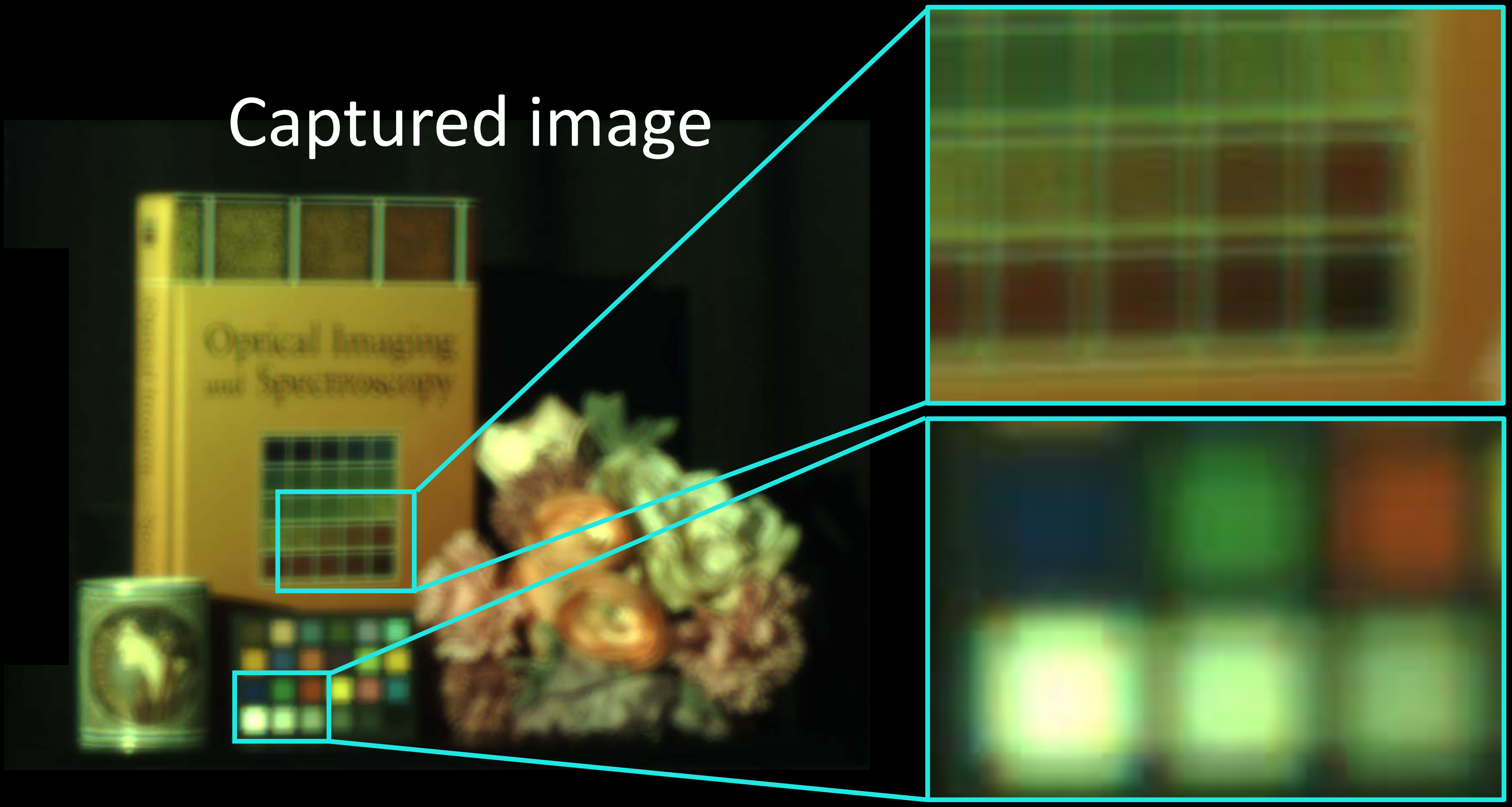
* (DOE simulation spec.) 1um xy-resolution, 100nm height resolution in 16 steps

Our DOE: Spectrally-Varying PSF

Our PSF

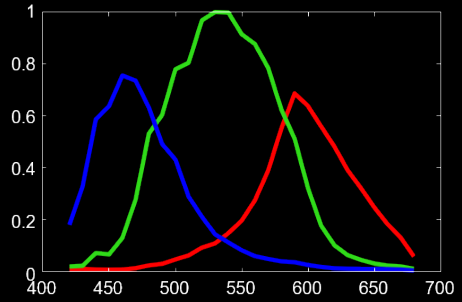


Captured image



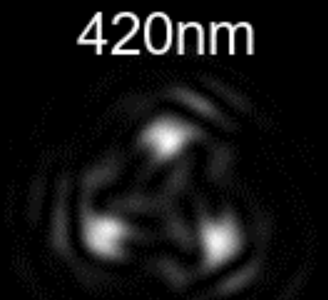
Hyperspectral Imaging Formulation

Input RGB image



Camera function

Hyperspectral image



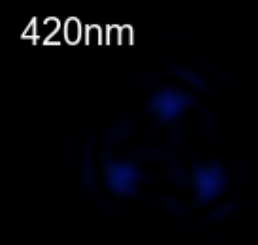
PSF

$$J_c(x,y) = \int \Omega_c(\lambda)(I_\lambda * p_\lambda)(x,y)\, d\lambda$$

Convolution

Optimization Problem

Input RGB image



Measurement matrix

Hyperspectral image

$$\hat{\mathbf{I}} = \arg\min_{\mathbf{I}} \left\| \mathbf{J} - \boldsymbol{\Phi}\mathbf{I} \right\|_2^2 + R(\mathbf{I})$$

Data term

Regularization term

(not differentiable)

Optimization Problem

- Using half-quadratic splitting (HQS)

$$(\hat{\mathbf{I}}, \hat{\mathbf{V}}) = \arg\min_{\mathbf{I},\mathbf{V}} \left\| \mathbf{J} - \mathbf{\Phi}\mathbf{I} \right\|_2^2 + \varsigma \left\| \underline{\mathbf{V}} - \mathbf{I} \right\|_2^2 + R(\underline{\mathbf{V}})$$

auxiliary variable

- The equation can be split into two subproblems

l-th half-quadratic splitting iteration

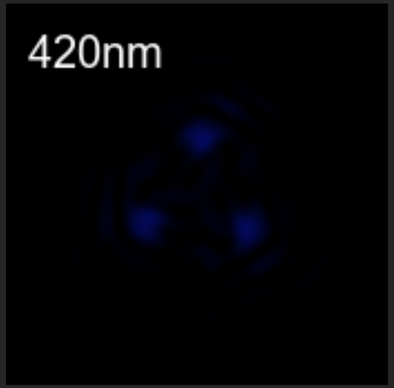
$$\mathbf{I}^{(l+1)} = \arg\min_{\mathbf{I}} \left\| \mathbf{J} - \mathbf{\Phi}\mathbf{I} \right\|_2^2 + \varsigma \left\| \mathbf{V}^{(l)} - \mathbf{I} \right\|_2^2 \quad (1)$$

$$\mathbf{V}^{(l+1)} = \arg\min_{\mathbf{V}} \varsigma \left\| \mathbf{V} - \mathbf{I}^{(l+1)} \right\|_2^2 + R(\mathbf{V}) \quad (2)$$

$\mathbf{I}$

$\mathbf{J}$

$\mathbf{\Phi}$



ς: penalty parameter

Iterative Optimization (Step 1)

- The first subproblem

$$\mathbf{I}^{(l+1)} = \underset{\mathbf{I}}{\arg\min} \left\| \mathbf{J} - \boldsymbol{\Phi}\mathbf{I} \right\|_2^2 + \varsigma \left\| \mathbf{V}^{(l)} - \mathbf{I} \right\|_2^2 \qquad (1)$$

- Solved by gradient descent

$$\mathbf{I}^{(l+1)} = \bar{\boldsymbol{\Phi}}\mathbf{I}^{(l)} + \varepsilon \mathbf{I}^{(0)} + \varepsilon\varsigma \mathbf{V}^{(l)}$$

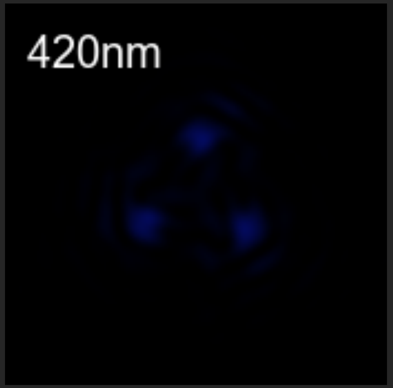
where $\bar{\Phi} = \left[\left(1 - \varepsilon\varsigma\right)\mathbf{1} - \varepsilon\, \Phi^{\mathrm{T}}\Phi \right]$

auxiliary variable

$\mathbf{I}$

$\mathbf{J}$

$\boldsymbol{\Phi}$



ε: step size

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Iterative Optimization (Step 2)

- The second subproblem

$$\mathbf{V}^{(l+1)} = \arg\min_{\mathbf{V}} \varsigma \left\| \mathbf{V} - \mathbf{I}^{(l+1)} \right\|_2^2 + R(\mathbf{V}) \qquad (2)$$

auxiliary variable

Unknown spectral prior

- reformulated as

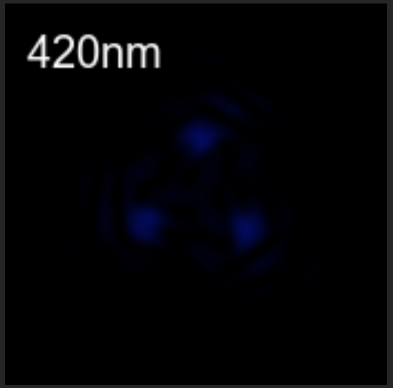
$$\mathbf{V}^{(l+1)} = S\left(\mathbf{I}^{(l+1)}\right)$$

- where *S()* is a neural network function

I

J

Φ



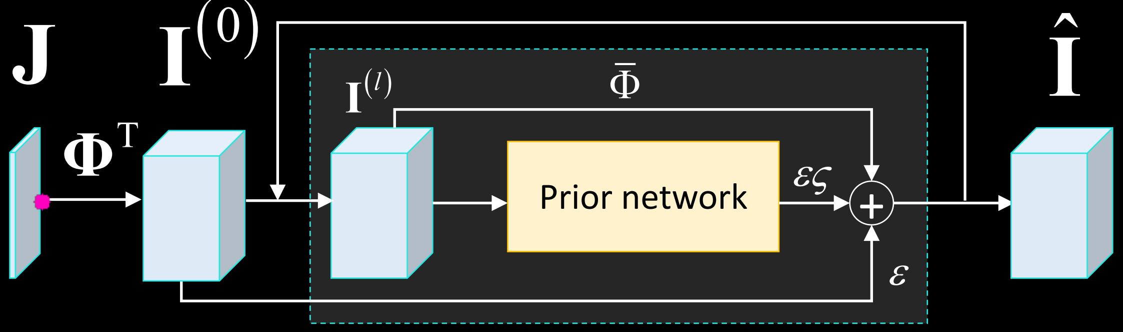
Optimization-based Unrolled Network

$$\mathbf{I}^{(l+1)} = \bar{\mathbf{\Phi}}\mathbf{I}^{(l)} + \varepsilon\mathbf{I}^{(0)} + \varepsilon\varsigma\mathbf{V}^{(l)}$$

where $\bar{\mathbf{\Phi}} = \left[(1-\varepsilon\varsigma)\mathbf{1} - \varepsilon\,\mathbf{\Phi}^{\mathrm{T}}\mathbf{\Phi}\right]$

$\mathbf{\Phi}$: measurement matrix

Input RGB image

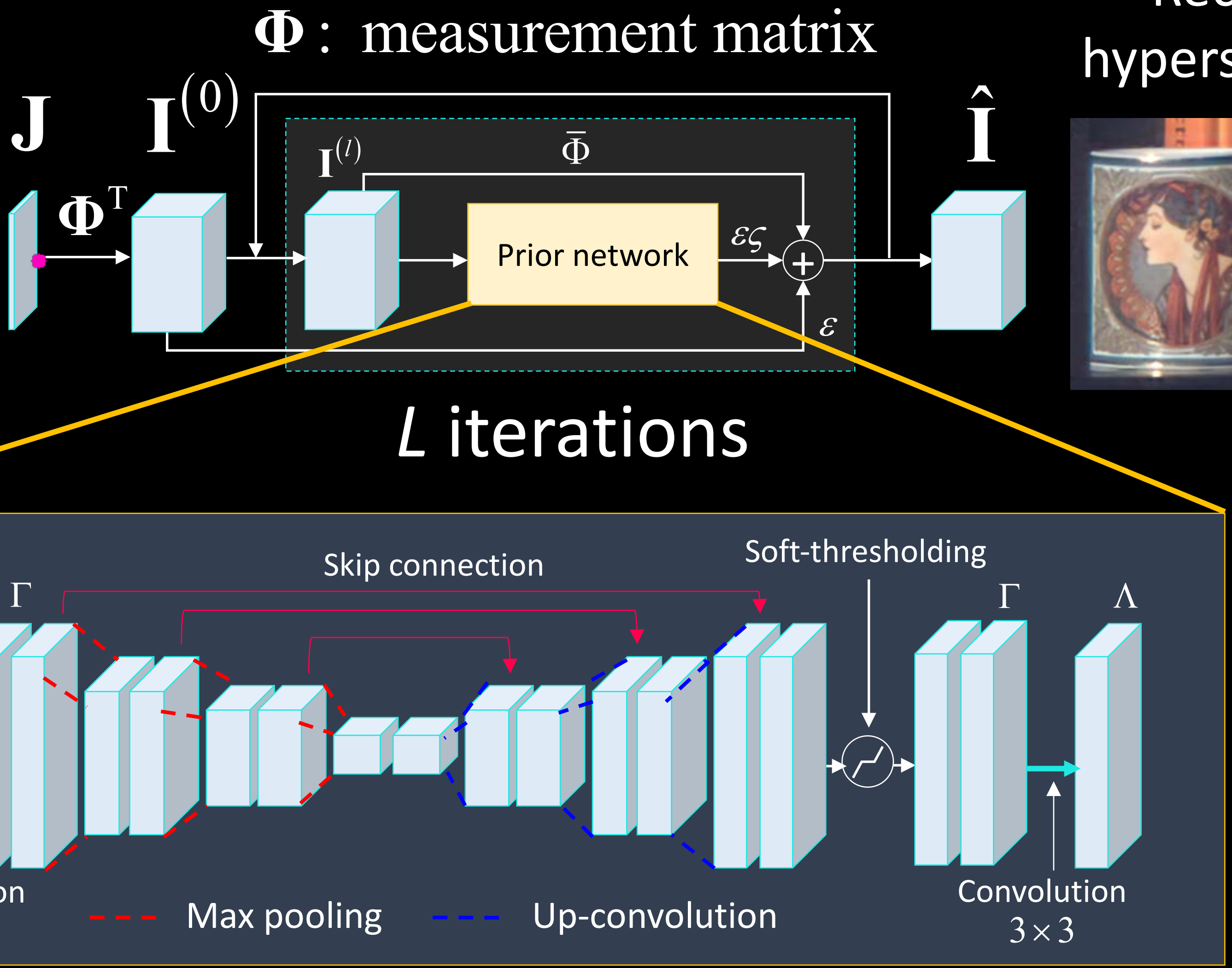


L iterations

Reconstructed hyperspectral image

U-net based Spatial-Spectral Prior Network

Input RGB image



Reconstructed hyperspectral image

$$\mathbf{V}^{(l)} = S\left(\mathbf{I}^{(l)}\right)$$

Γ : feature size (64), Λ : number of wavelengths (25)

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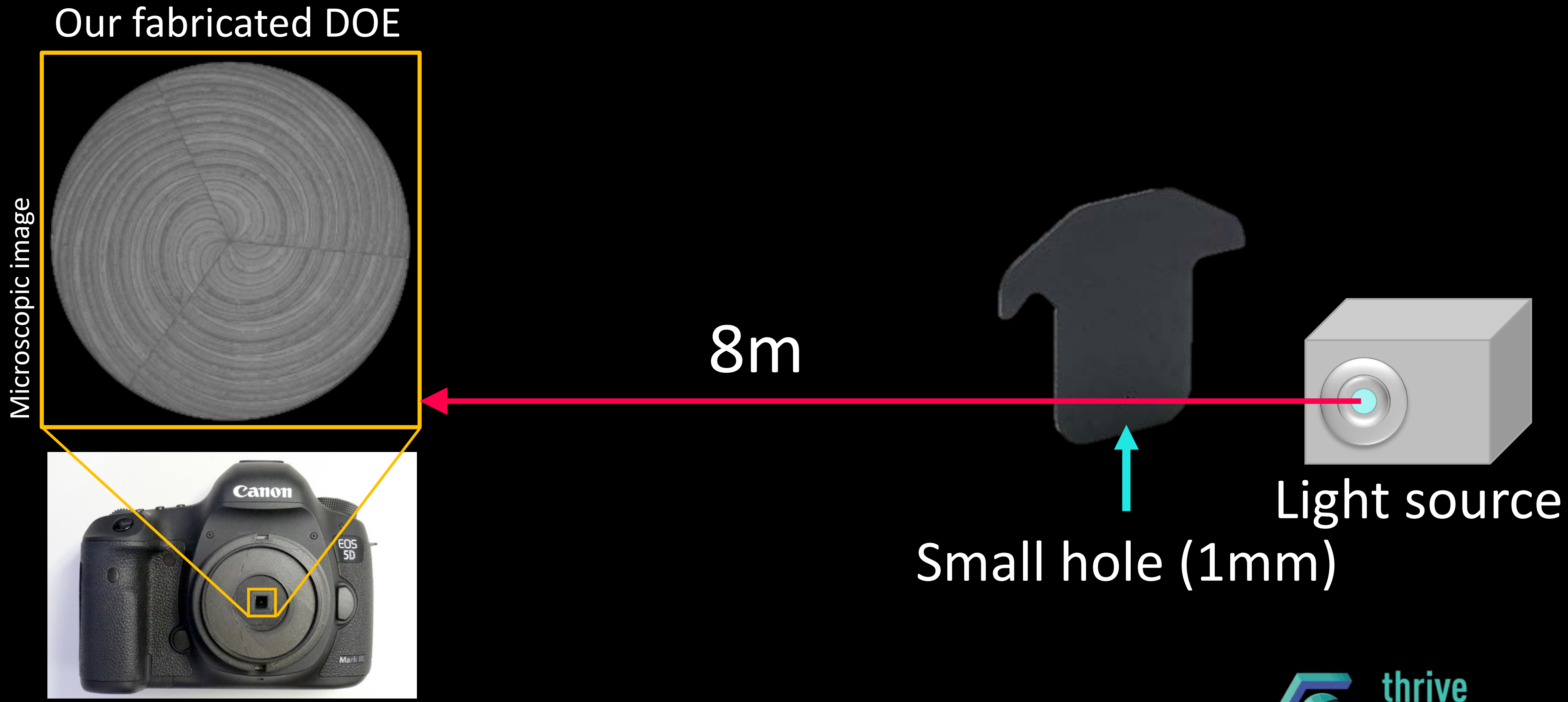
Datasets

- Training dataset
  - Harvard dataset [Chakrabarti and Zickler 2011]
  - ICVL dataset [Arad and Ben-Shahar 2016]
  - KAIST dataset [Choi et al. 2017]
  - Augmentation: half/original/double resolution of 238 hyperspectral images (= 714 hyperspectral images in total)
  - 30,000 patches of size $256 \times 256 \times 25$ in total
  - Gaussian noise with a standard deviation of 0.005
- Test dataset
  - 10 images extracted from the KAIST dataset beforehand

Spectral Calibration of Real PSF



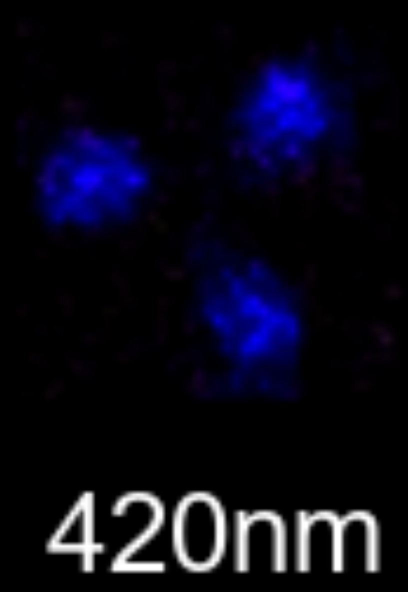
Spectral Calibration of Real PSF

Our fabricated DOE

Microscopic image

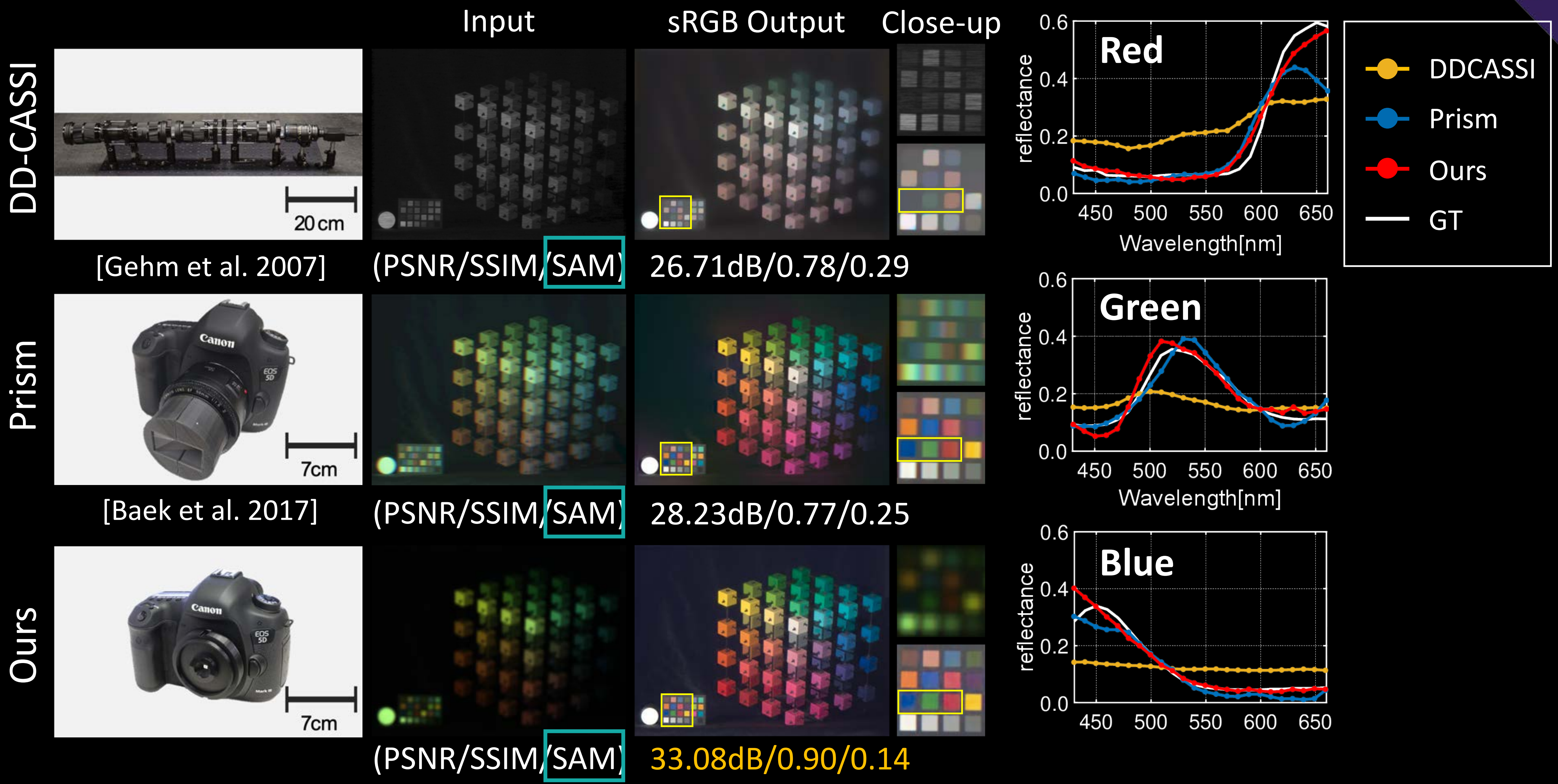
Synthetic PSFs

Measured PSFs

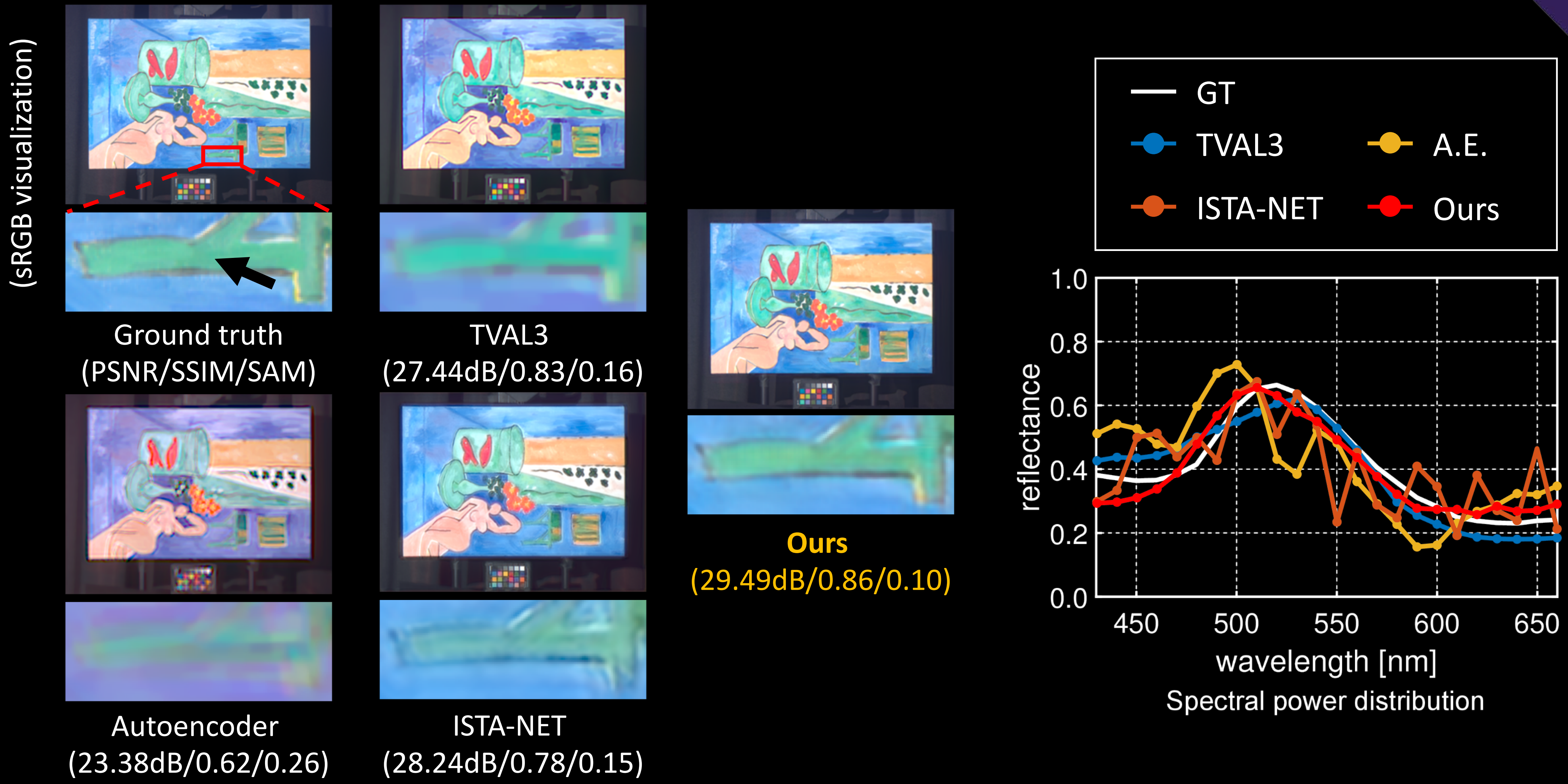


Results

Comparison with Other Imaging Systems



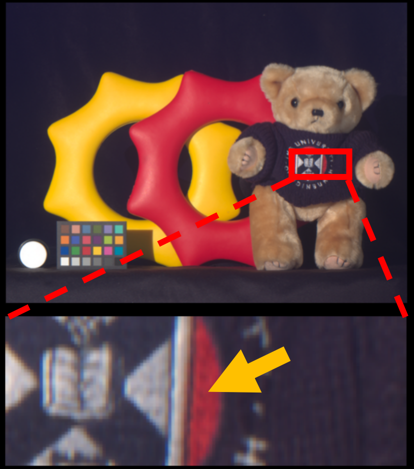
Comparison with Other Recon. Algorithms



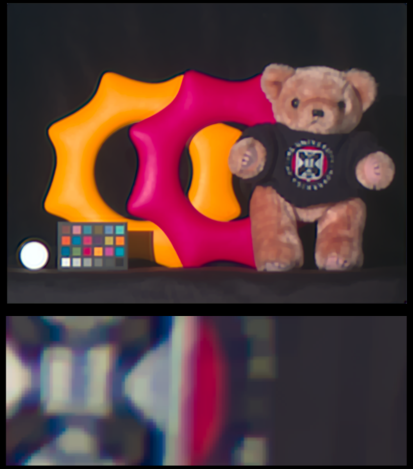
Spectral power distribution

Comparison with Other Recon. Algorithms

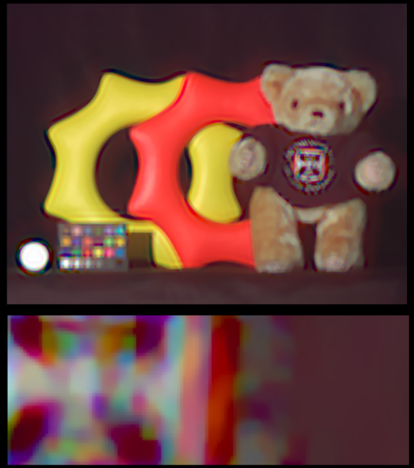
(sRGB visualization)



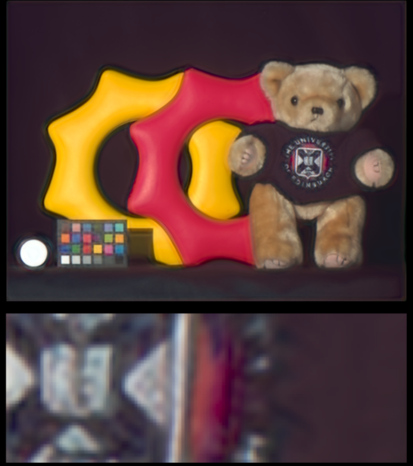
Ground truth
(PSNR/SSIM/SAM)



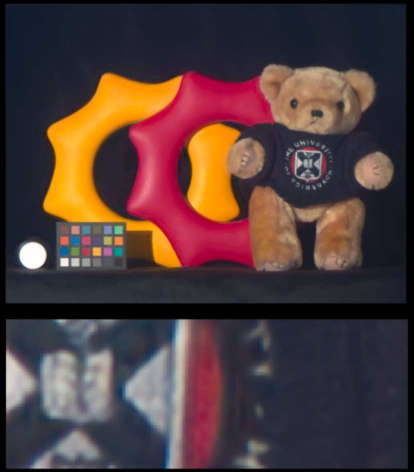
TVAL3
(28.52dB/0.84/0.18)



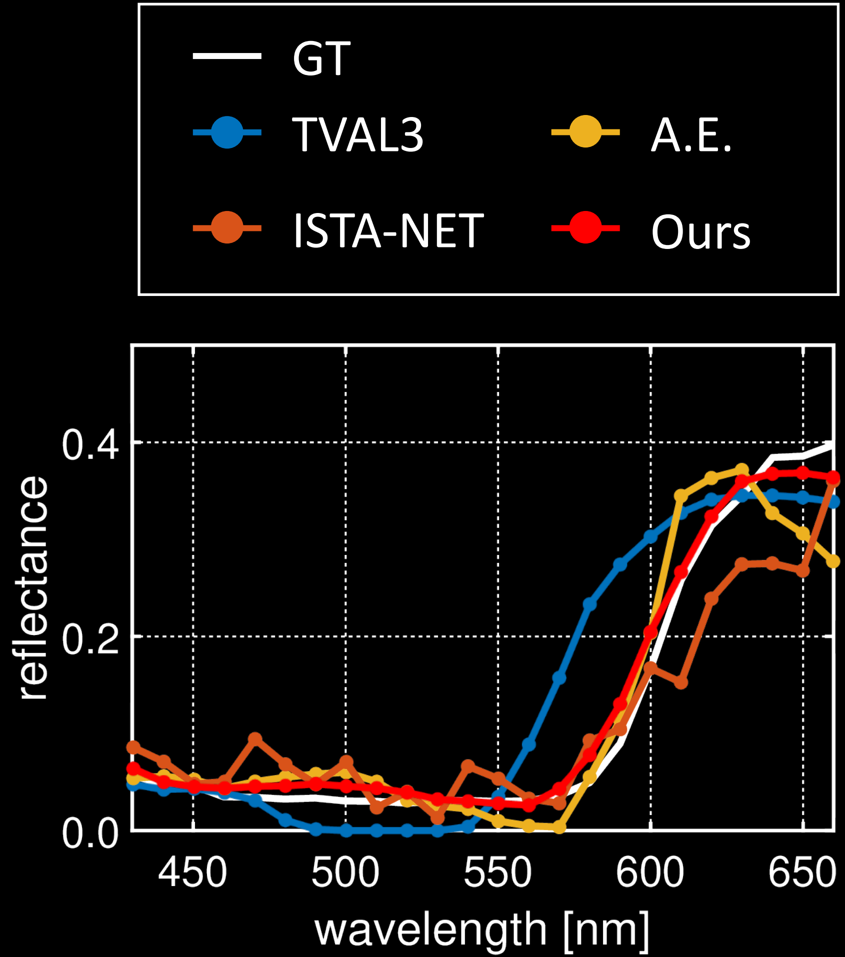
Autoencoder
(23.42dB/0.75/0.24)



ISTA-NET
(31.96dB/0.86/0.16)

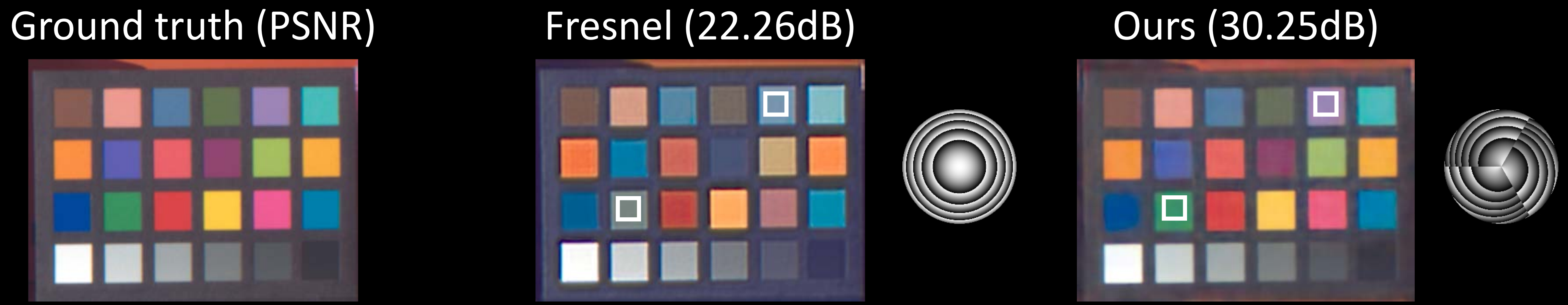


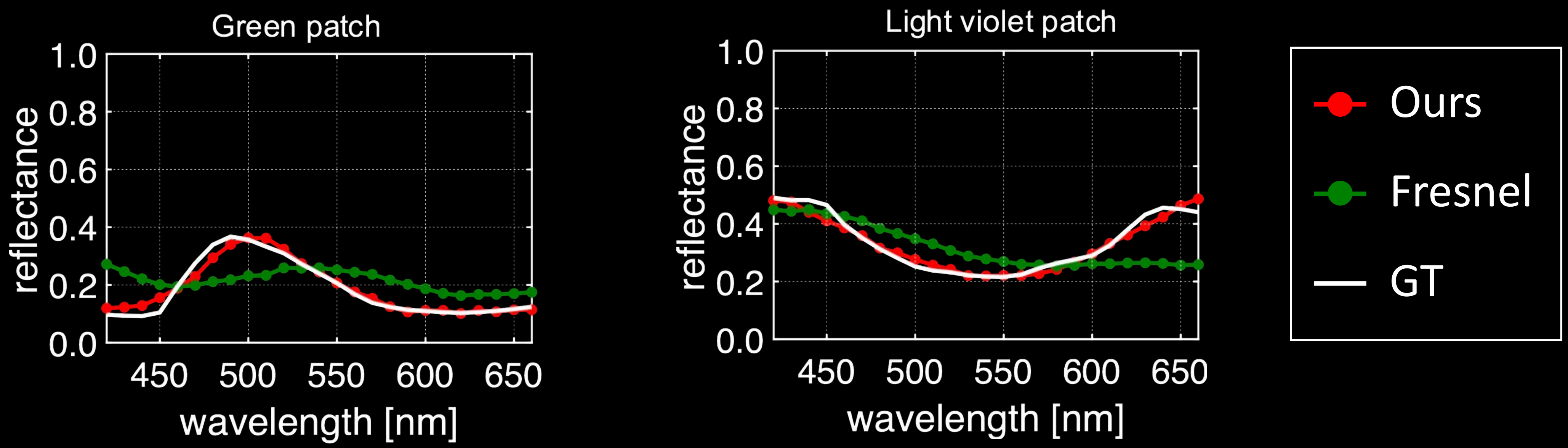
Ours
(33.93dB/0.92/0.11)



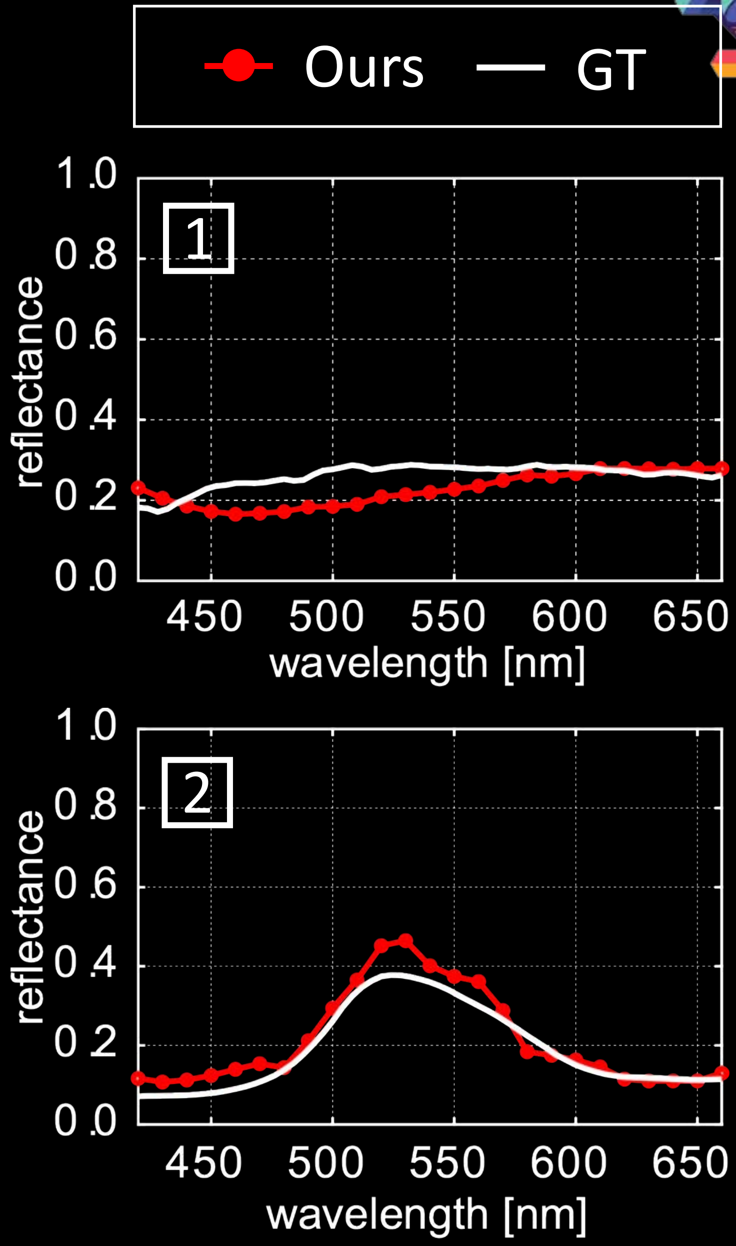
Spectral power distribution

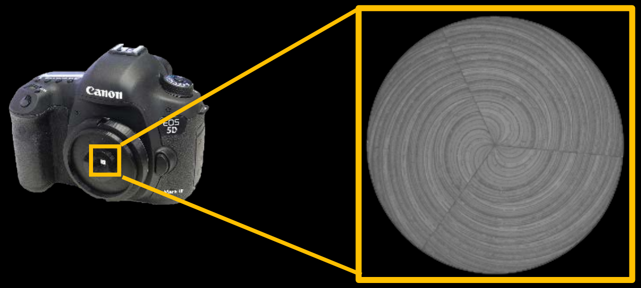
Comparison with Fresnel Lens





Real Scene Results





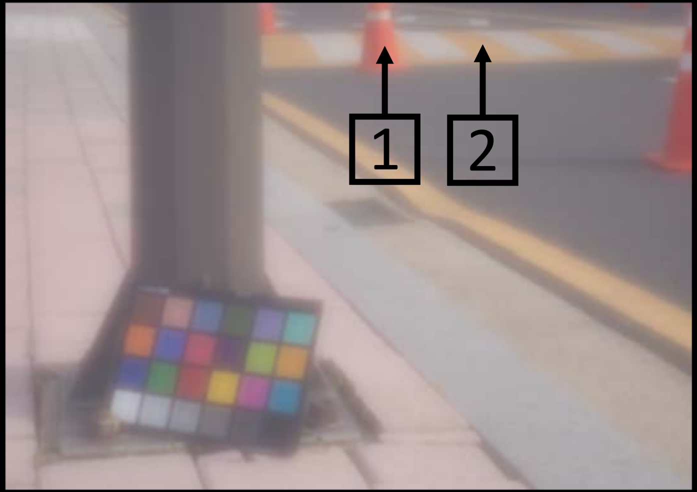
Our prototype

Spectroradiometer
SpectralScan PR-655

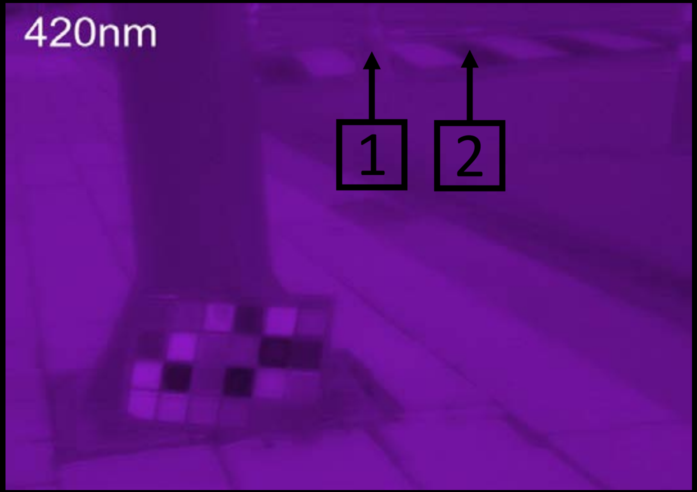
Ground truth

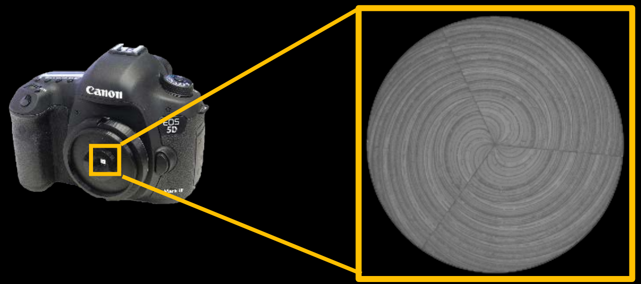
Real Scene Results

Input



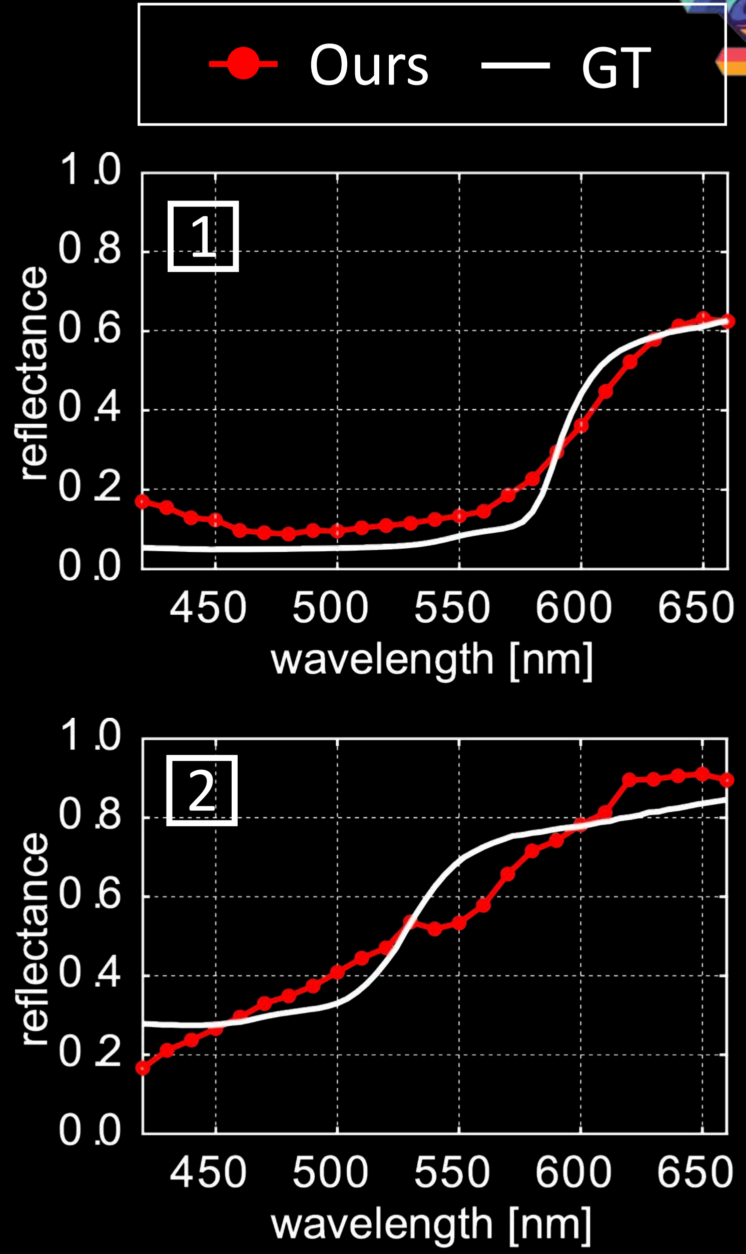
Reconstructed spectral image





Our prototype

Ground truth

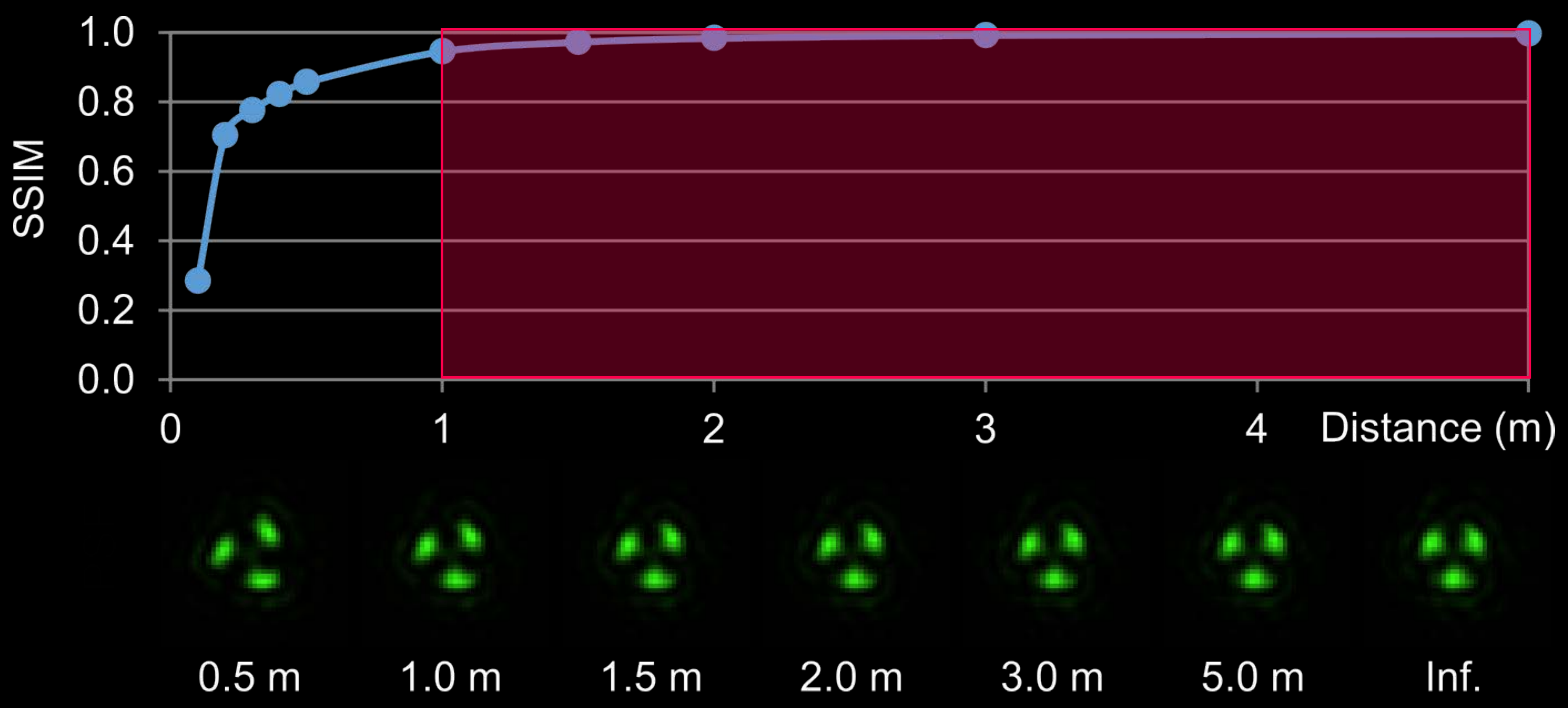


Discussion: PSF Invariance

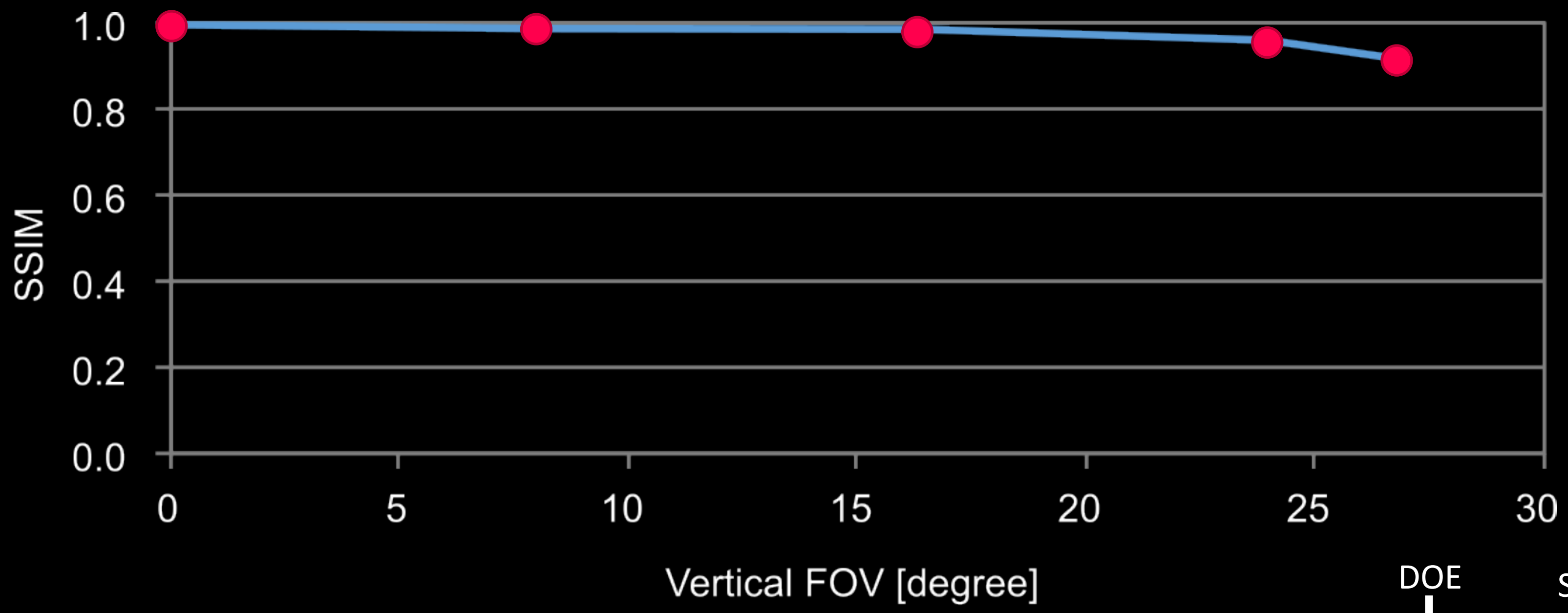
Depth invariance

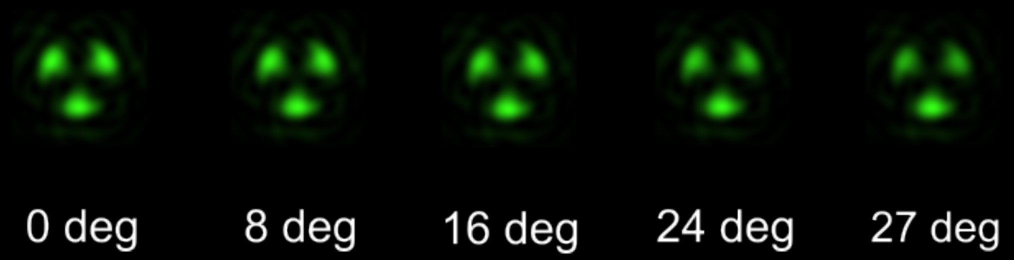
Incident angle invariance

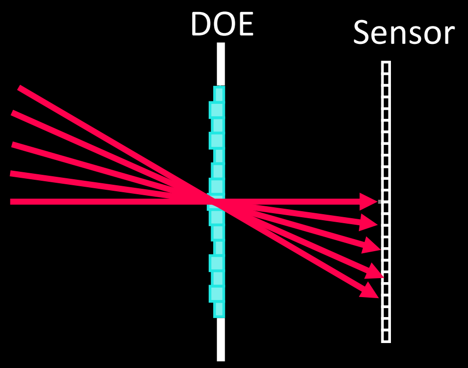
Discussion: Depth Invariance



Discussion: Incident Angle Invariance







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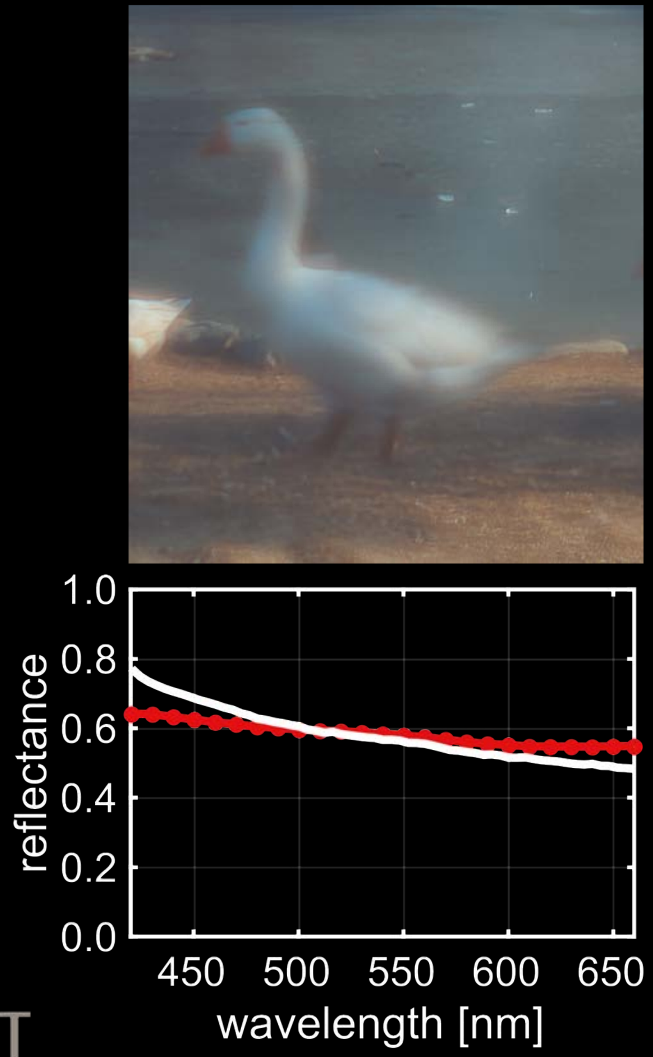
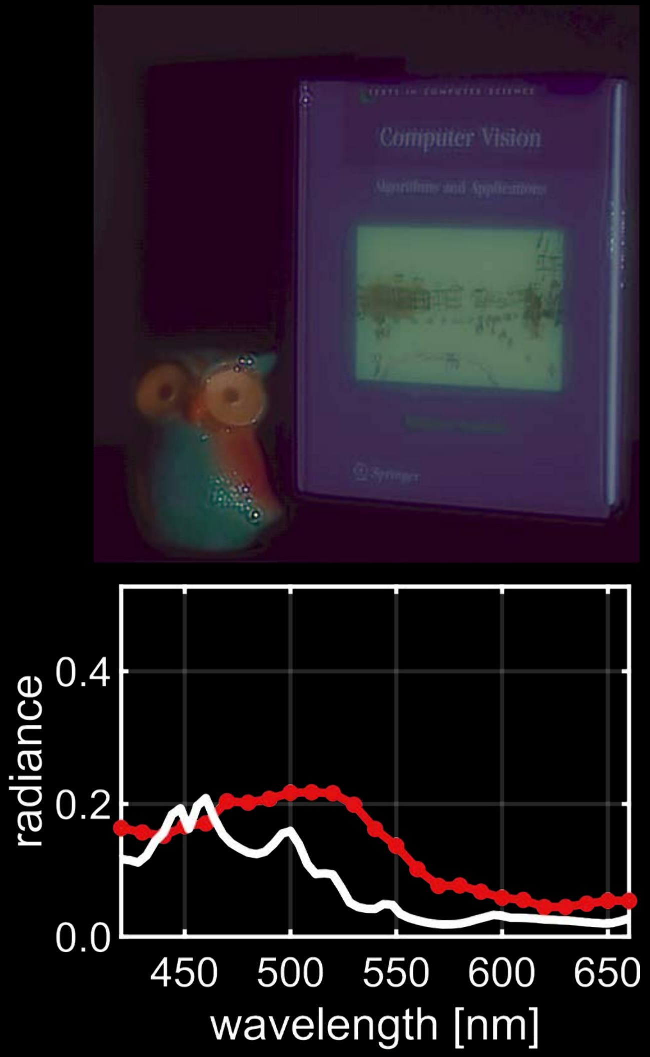
Limitation

Lack of edges



High-frequency illumination



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Conclusion

- First diffraction-based hyperspectral imaging that consists of a single optical element and a bare sensor
  - Diffractive imaging lens to achieve both imaging and dispersion with a single DOE
  - End-to-end hyperspectral reconstruction network based on the unrolled architecture of an optimization procedure

Thank you!

Project website:
http://vclab.kaist.ac.kr/siggraph2019/