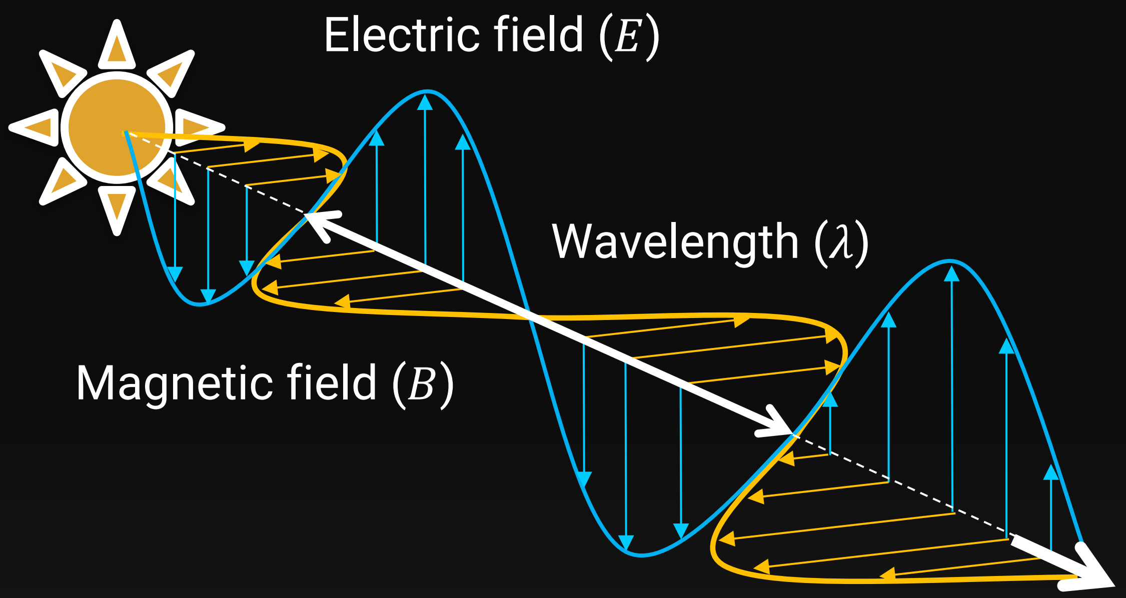
SPARSE ELLIPSOMETRY: PORTABLE ACQUISITION OF POLARIMETRIC SVBRDF AND SHAPE WITH UNSTRUCTURED FLASH PHOTOGRAPHY

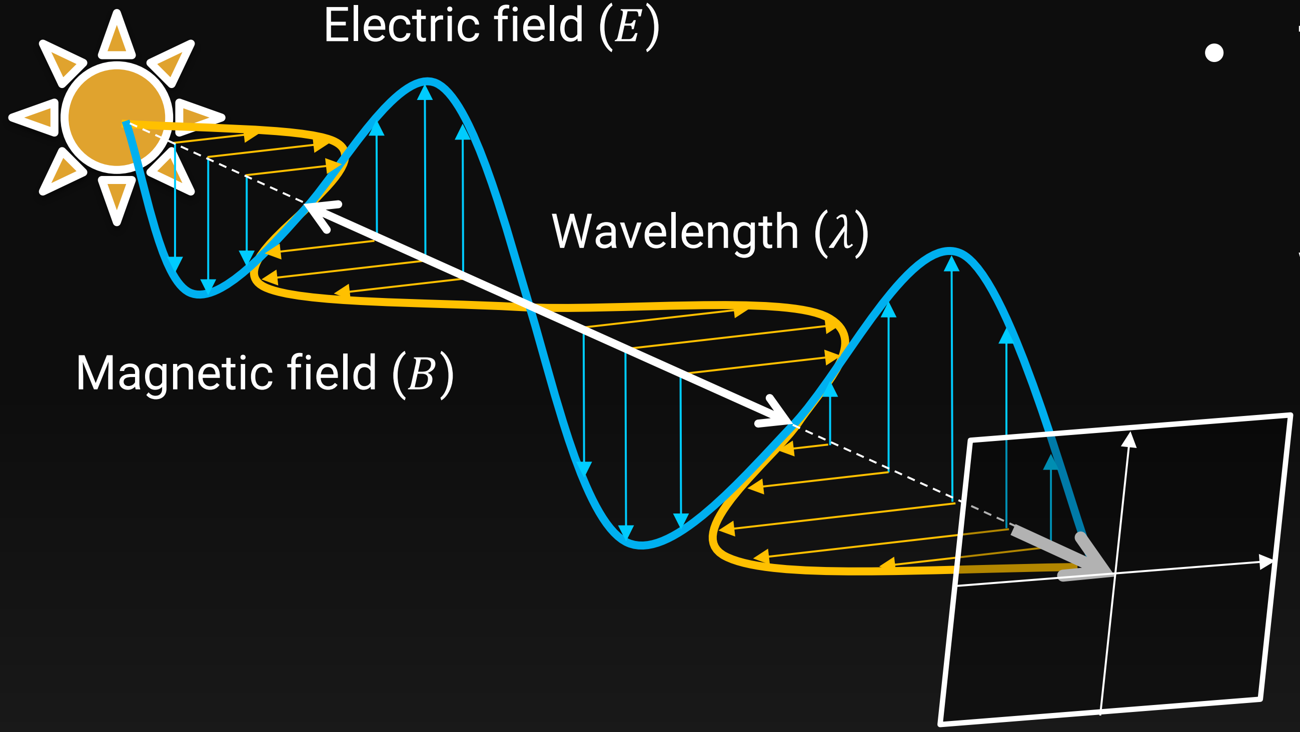
INSEUNG HWANG, DANIEL S. JEON, ADOLFO MUÑOZ, DIEGO GUTIERREZ, XIN TONG, MIN H. KIM

Polarization



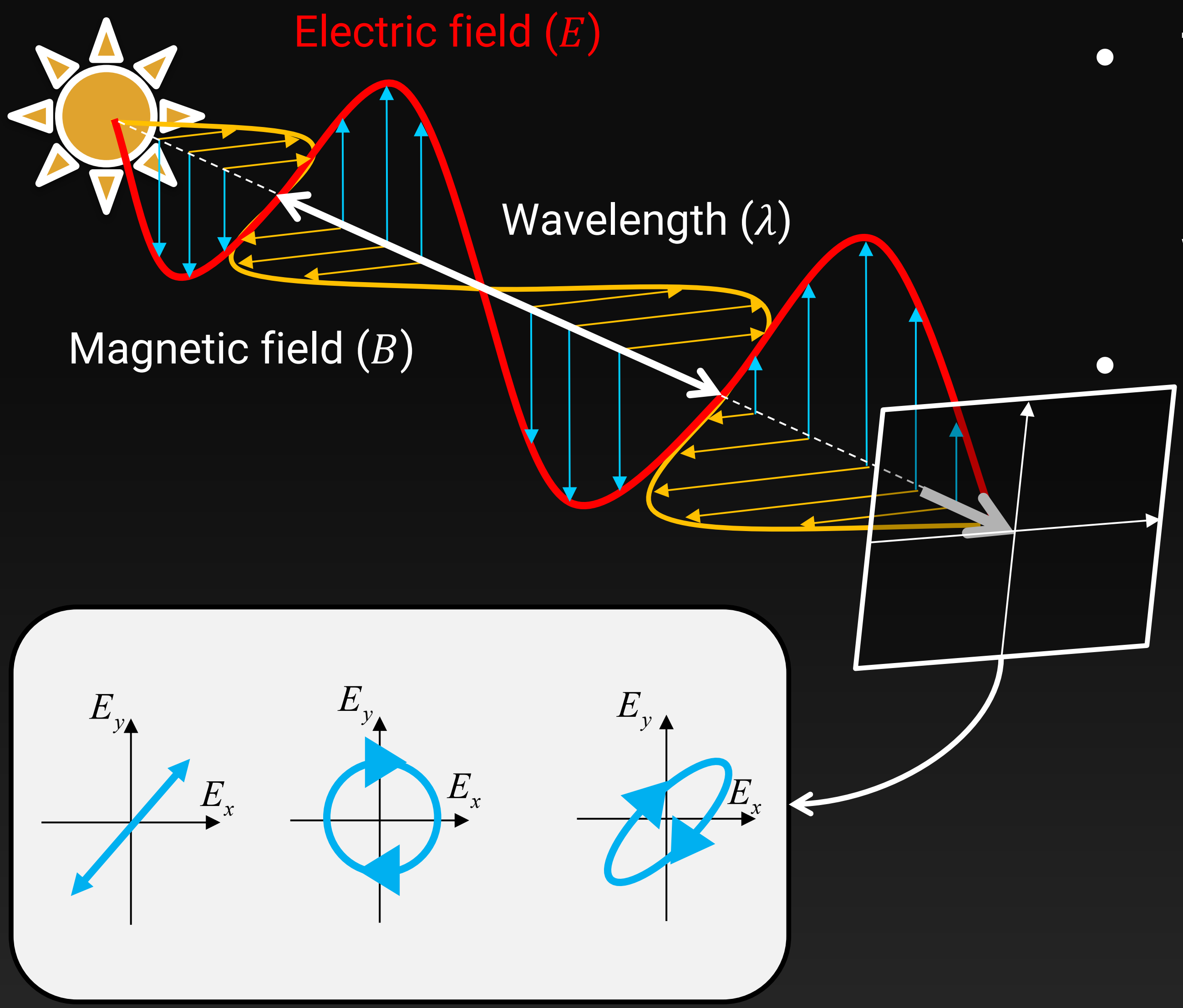
- Light is an electro-magnetic wave

Polarization



- Light is an electro-magnetic wave
- The direction of oscillation is perpendicular to the direction of the wave

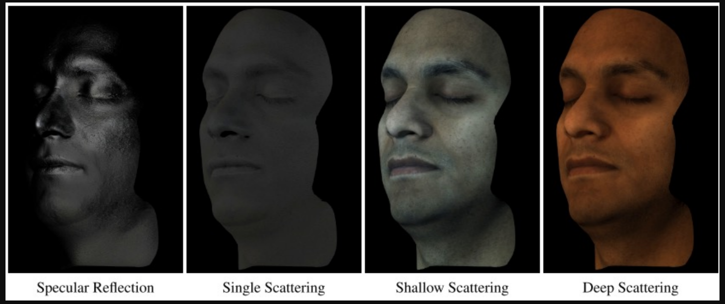
Polarization



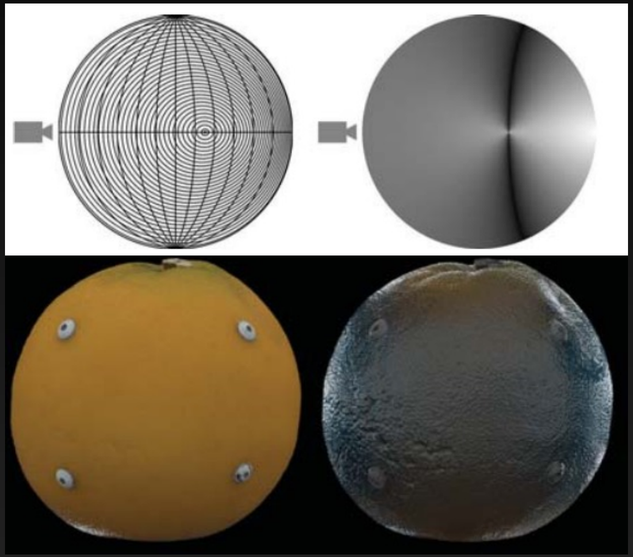
- Light is an electro-magnetic wave
- The direction of oscillation is perpendicular to the direction of the wave
- Polarization is the direction of the electric field

Related work

Reflection separation

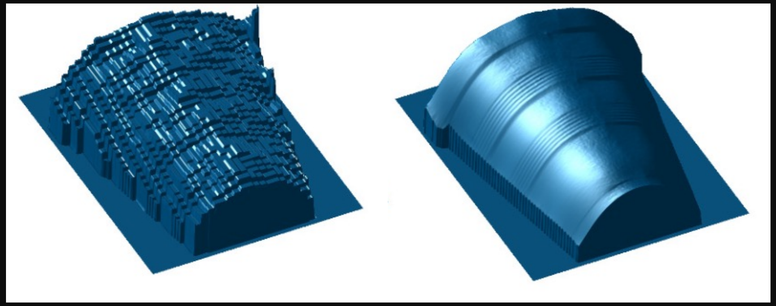


[Ghosh et al. ‘08]

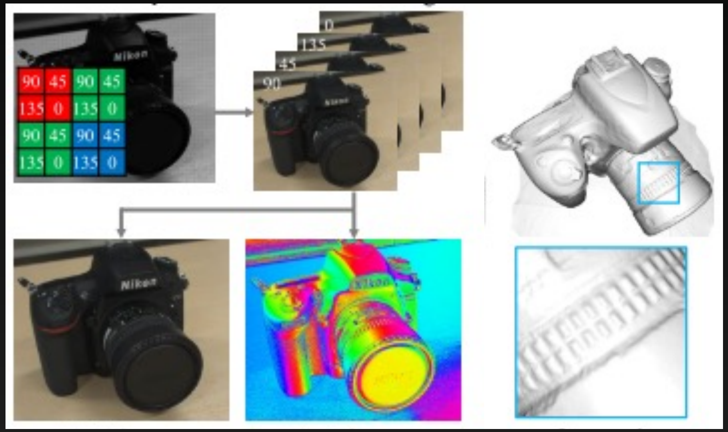


[Ma et al. ‘07]

Shape acquisition



[Kadambi et al. ‘15]

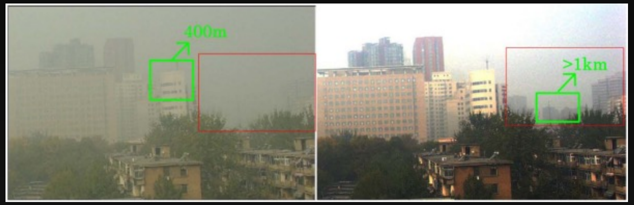


[Zhao et al. ‘20]

Depth acquisition

[Baek et al. ‘16]

Dehazing



[Liu et al. ‘15]

Image editing

[del Molino and Muñoz ‘19]

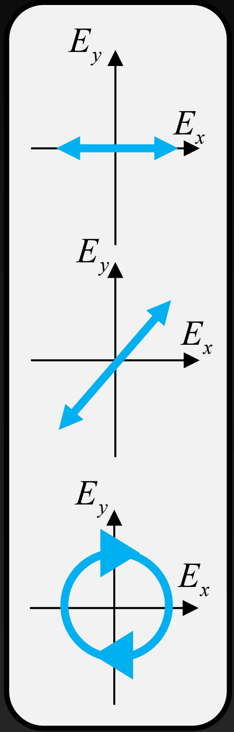
Stokes vector and Mueller matrix

$$\mathbf{s}_o = \mathbf{M} \quad \mathbf{s}_i$$

Stokes vector

$$\mathbf{s} = \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix}$$

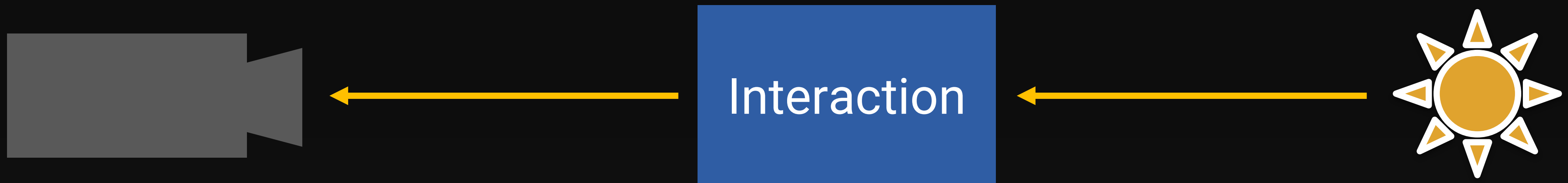
- S_0: Intensity
- S_1: Horizontal/vertical
- S_2: Diagonal/antidiagonal
- S_3: Circular



Mueller matrix

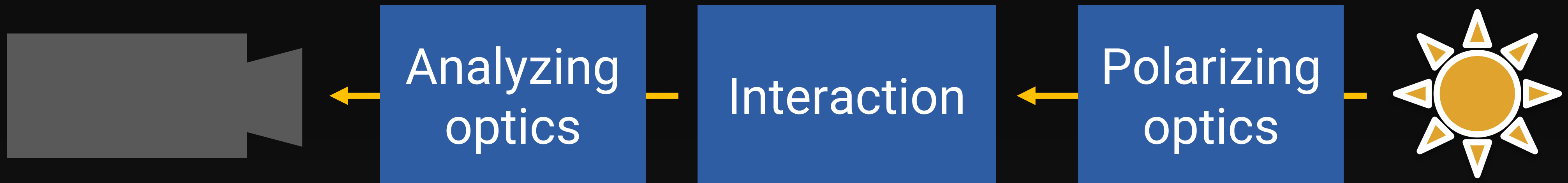
$$\mathbf{M} = \begin{bmatrix} M_{00} & M_{01} & M_{02} & M_{03} \\ M_{10} & M_{11} & M_{12} & M_{13} \\ M_{20} & M_{21} & M_{22} & M_{23} \\ M_{30} & M_{31} & M_{32} & M_{33} \end{bmatrix}$$

Ellipsometry



$$\mathbf{s}_o = \mathbf{M} \mathbf{s}_i$$

Ellipsometry



$$I = \mathbf{a} \; \mathbf{M} \; \mathbf{p}$$

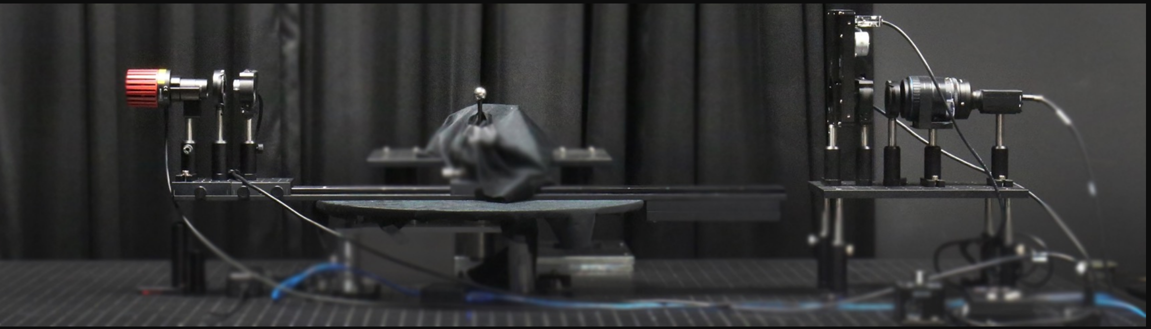
Ellipsometry

Known

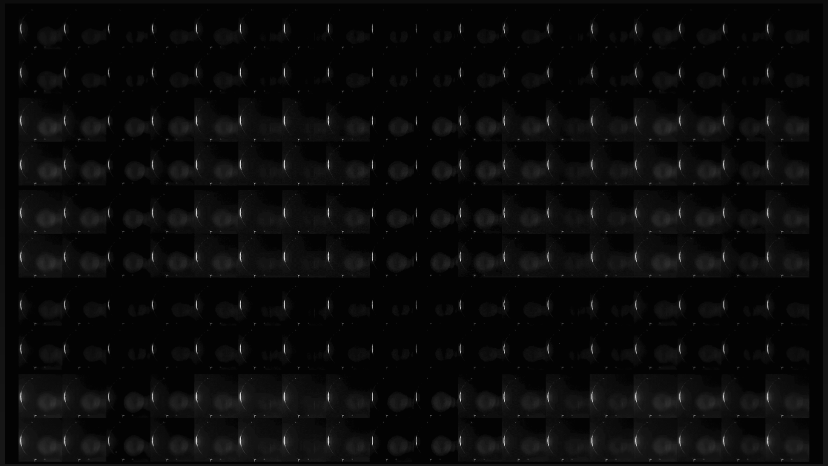
Unknown

$$\min_{\mathbf{M}} \sum_{k=1}^{K} \left\{ I_k - \left[\mathbf{a}(\theta_k) \mathbf{M} \, \mathbf{p}(\theta'_k) \right] \right\}^2$$

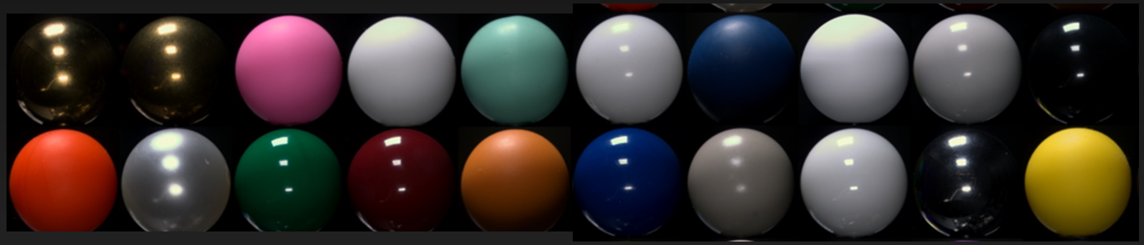
Challenges for polarimetric BRDF acquisition



Benchtop system [Baek et al. ’20]



2-5 days captures

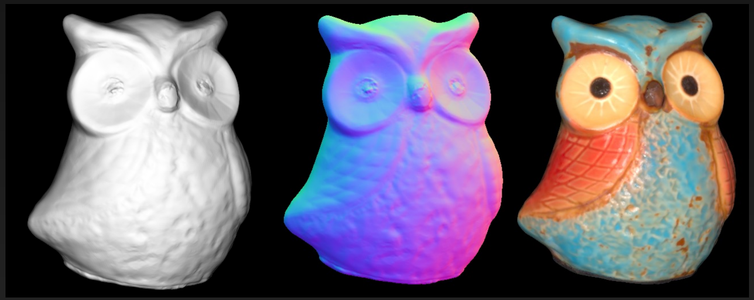


Uniform material and sphere shape

Our approach

Hand-held device

20-30 minutes captures



Spatially-varying pBRDF in various shapes

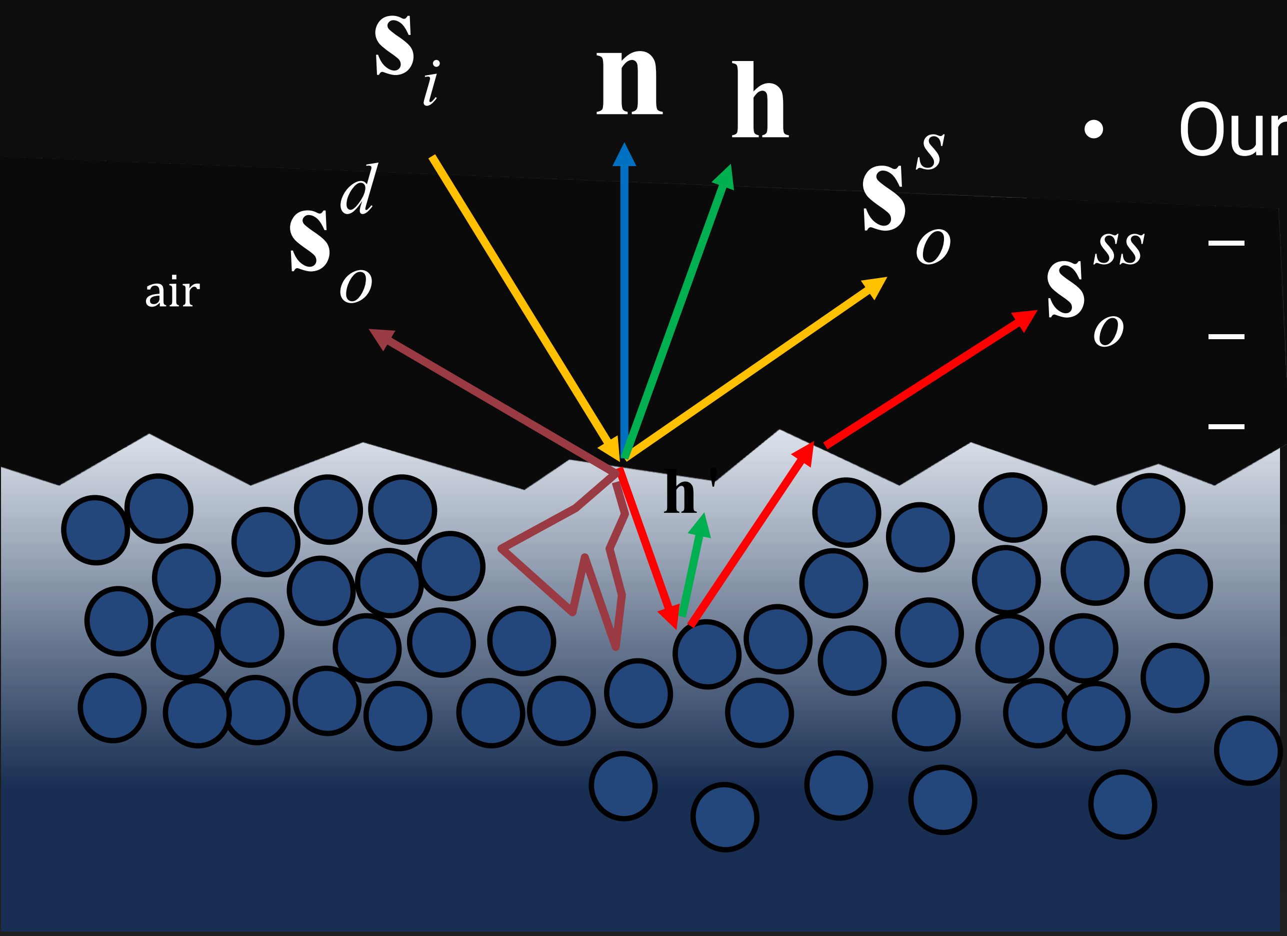
Our approach

3D Muller matrix

Novel view and lighting rendering

Method

Polarimetric reflectance model



- pBRDF: $\mathbf{s}_o = \mathbf{P}(\omega_i, \omega_o)\mathbf{s}_i$

- Our pBRDF includes 3 types of reflection
  - Diffuse
  - Specular
  - Single scattering

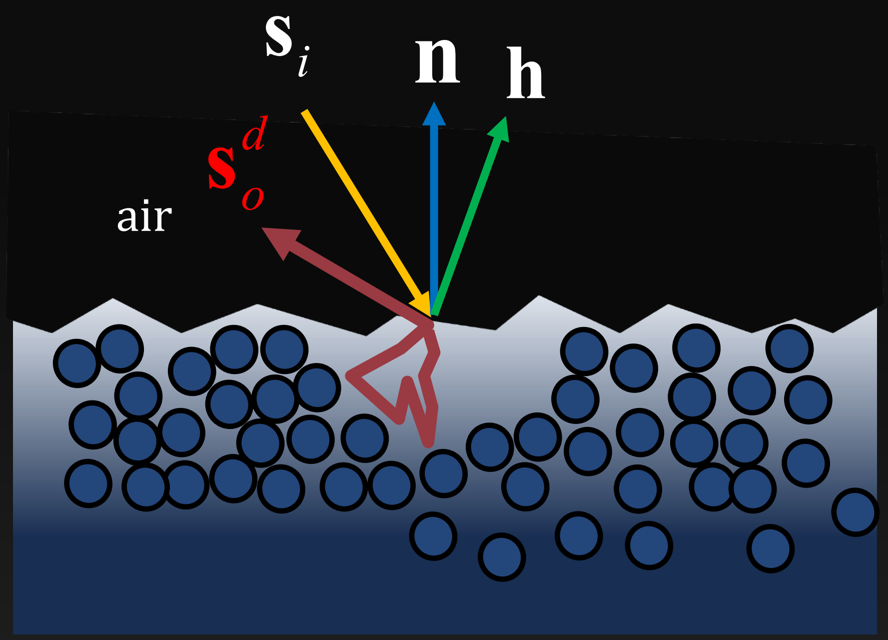
$$\mathbf{P} = \mathbf{P}^d + \mathbf{P}^s + \mathbf{P}^{ss}$$

Diffuse reflectance model

Fresnel transmission

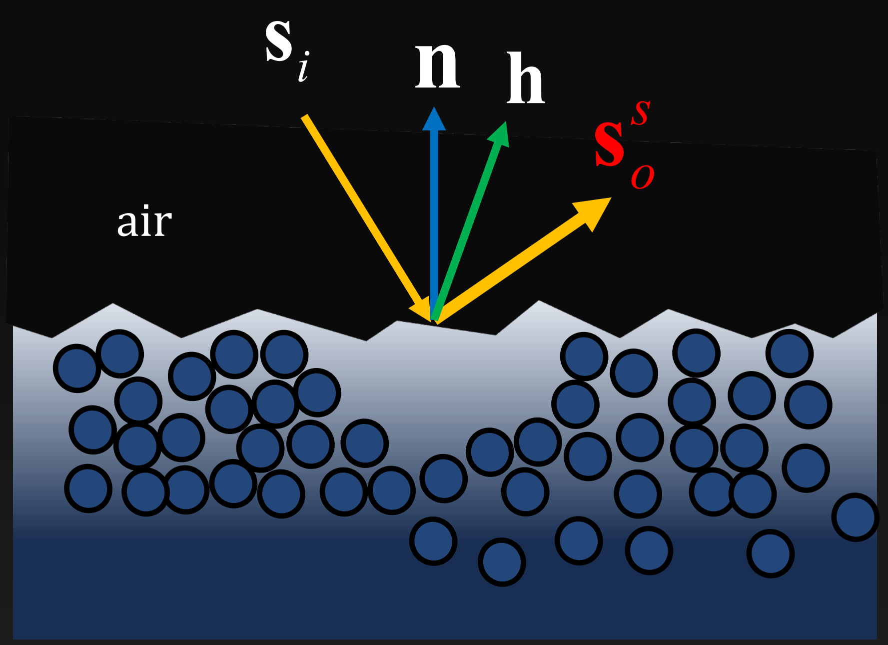
$$\mathbf{P}^d = \mathbf{C}_{n\to o}\mathbf{F}^T\mathbf{D}\mathbf{F}^T\mathbf{C}_{i\to n}$$

Coordinate conversion Depolarization



- Diffuse reflection includes
  - transmission (air → medium)
  - depolarization by multiple scattering
  - transmission (medium → air)

Specular reflectance model



Fresnel reflection

$$\mathbf{P}^s = \kappa_s \mathbf{C}_{h\to o}\mathbf{F}^R\mathbf{C}_{i\to h}$$

Coordinate conversion

κ_s : specular reflection term $\kappa_s = \rho_s \dfrac{DG}{4(\mathbf{n}\cdot\omega_i)(\mathbf{n}\cdot\omega_o)}$

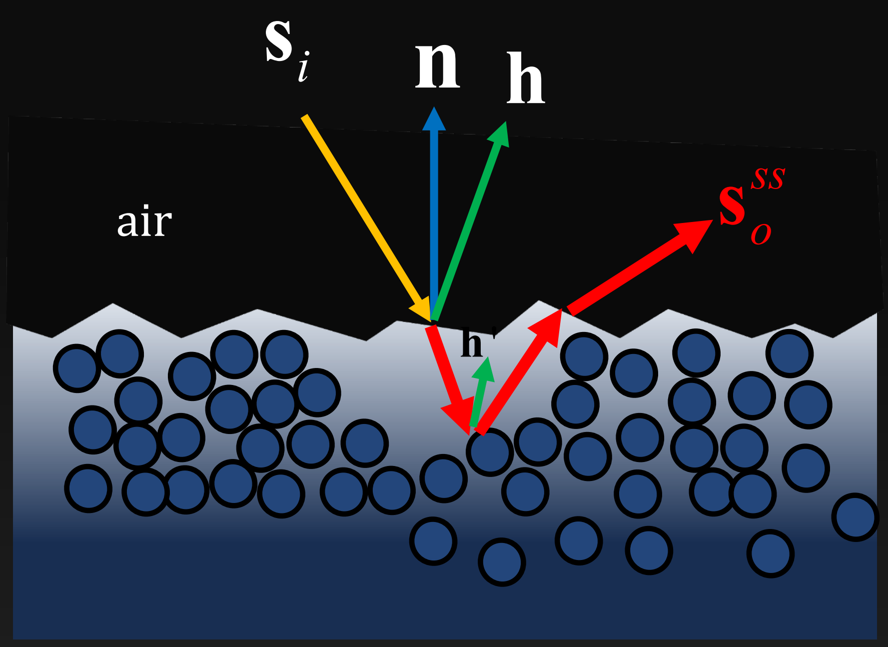
- Specular reflection is described as
  - a single-bounce reflection

Single scattering model

Fresnel transmission (air→media)

$$\mathbf{P}^{ss} = r_{ss}\mathbf{C}_{n\to o}\mathbf{F}^{T}\mathbf{C}_{h'\to n}\mathbf{F}^{R'}\mathbf{C}_{n\to h'}\mathbf{F}^{T}\mathbf{C}_{i\to n}$$

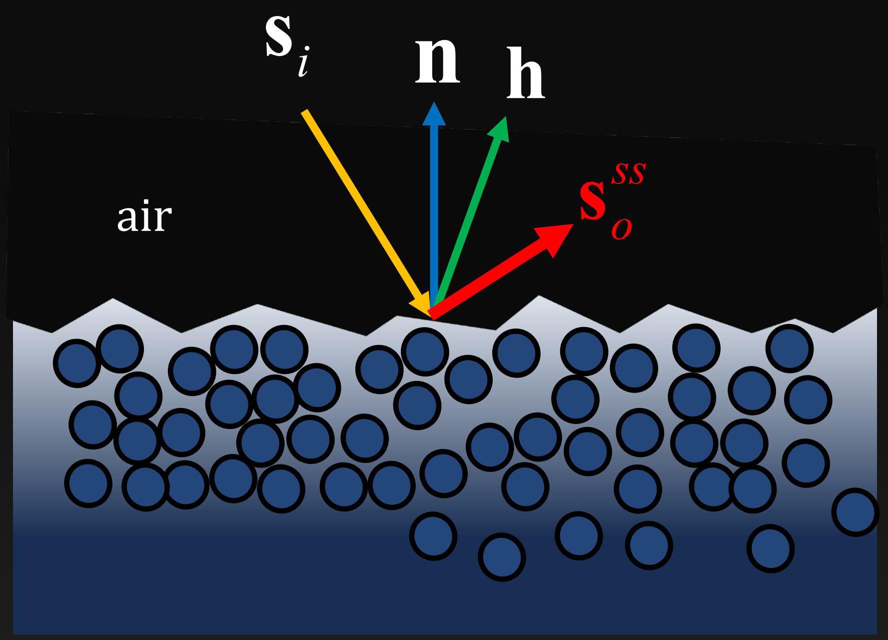
Coordinate conversion Fresnel reflection (media→particle)



r_{ss} : single scattering BRDF

- Single scattering includes
  - transmission (air → medium)
  - scattering reflection
  - transmission (medium → air)

Practical single scattering model



Fresnel reflection

$$\mathbf{P}^{ss} = \kappa_{ss} \mathbf{C}_{n\to o} \mathbf{F}^R \mathbf{C}_{i\to n}$$

Coordinate conversion

κ_{ss} : single scattering reflection term $\kappa_{ss} = \rho_{ss} \dfrac{DG}{4(\mathbf{n}\cdot\boldsymbol{\omega}_i)(\mathbf{n}\cdot\boldsymbol{\omega}_o)}$

- Practical single scattering light transport
  - The similar polarization state with specular
  - Independent roughness
  - Colored albedo

Our capture device

- Geometry: near-coaxial setup
  - ~3.5° angle difference
- Input: 100-300 flash photographs

Coaxial acquisition system

- The Mueller matrix model can be simplified in the coaxial system

$$\mathbf{P} \approx \begin{bmatrix} \rho_d T^+ T^+ + \kappa_s R^+ + \kappa_{ss} R^+ & -\rho_d T^- T^+ \beta & \rho_d T^- T^+ \alpha & 0 \\ -\rho_d T^- T^+ \beta & \kappa_s R^+ + \kappa_{ss} R^+ & 0 & 0 \\ -\rho_d T^- T^+ \alpha & 0 & -\kappa_s R^+ - \kappa_{ss} R^+ & 0 \\ 0 & 0 & 0 & -\kappa_s R^+ - \kappa_{ss} R^+ \end{bmatrix}$$

Diffuse shading

Specular and single scattering

Diffuse polarization (sine)

Diffuse polarization (cosine)

Coaxial acquisition system

- The Mueller matrix model can be simplified in the coaxial system

$$\mathbf{P} \approx \begin{bmatrix} \rho_d T^+ T^+ + \kappa_s R^+ + \kappa_{ss} R^+ & -\rho_d T^- T^+ \beta & \rho_d T^- T^+ \alpha \\ -\rho_d T^- T^+ \beta & \kappa_s R^+ + \kappa_{ss} R^+ & 0 \\ -\rho_d T^- T^+ \alpha & 0 & -\kappa_s R^+ - \kappa_{ss} R^+ \end{bmatrix}$$

Diffuse shading

Specular and single scattering

Diffuse polarization (sine)

Diffuse polarization (cosine)

Coaxial acquisition system

- The Mueller matrix model can be simplified in the coaxial system

$$\mathbf{P} \approx \begin{bmatrix} DS + SS & -DP\beta & DP\alpha \\ -DP\beta & SS & 0 \\ -DP\alpha & 0 & -SS \end{bmatrix}$$

Diffuse shading

Specular and single scattering

Diffuse polarization (sine)

Diffuse polarization (cosine)

DS: Diffuse shading component

SS: Specular & single scattering component

$DP\alpha$: Diffuse polarization sine component

$DP\beta$: Diffuse polarization cosine component

Polarization camera input

- 4 different linear polarization images in a single shot
- Captured input:

Diffuse shading

$$I^d = DS = 2I_{90}$$

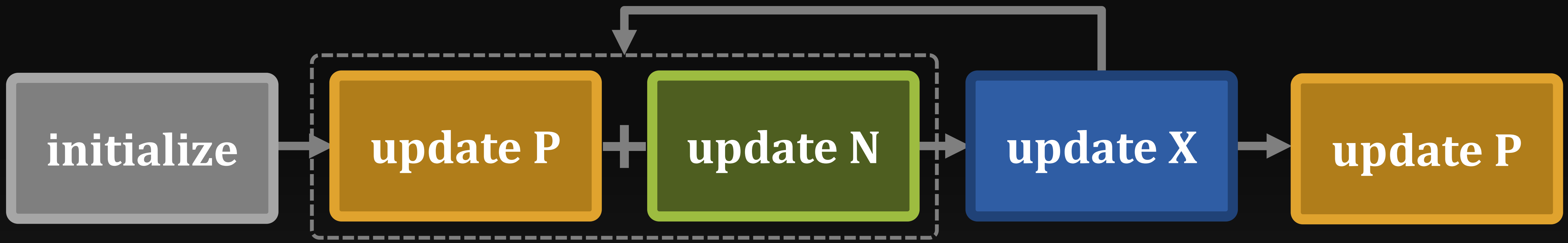
Diffuse polarization (sine)

$$I^\alpha = DP\alpha = I_{135} - I_{45}$$

Specular & single scattering + diffuse polarization (cosine)

$$I^s = SS - DP\beta = I_0 - I_{90}$$

Optimization overview



Optimizing polarimetric BRDF and normal

$$\min_{\eta,\sigma_s,\sigma_{ss},\rho_s,\rho_{ss},\rho_d,\mathbf{n}} \left(\lambda_1 \mathrm{L}_\psi + \lambda_2 \mathrm{L}_d + \lambda_3 \mathrm{L}_s + \lambda_4 \mathrm{L}_\phi \right)$$

L_ψ : refractive index loss

L_s : specular and single scattering loss

L_d : diffuse loss

L_ϕ : normal loss

Refractive index loss

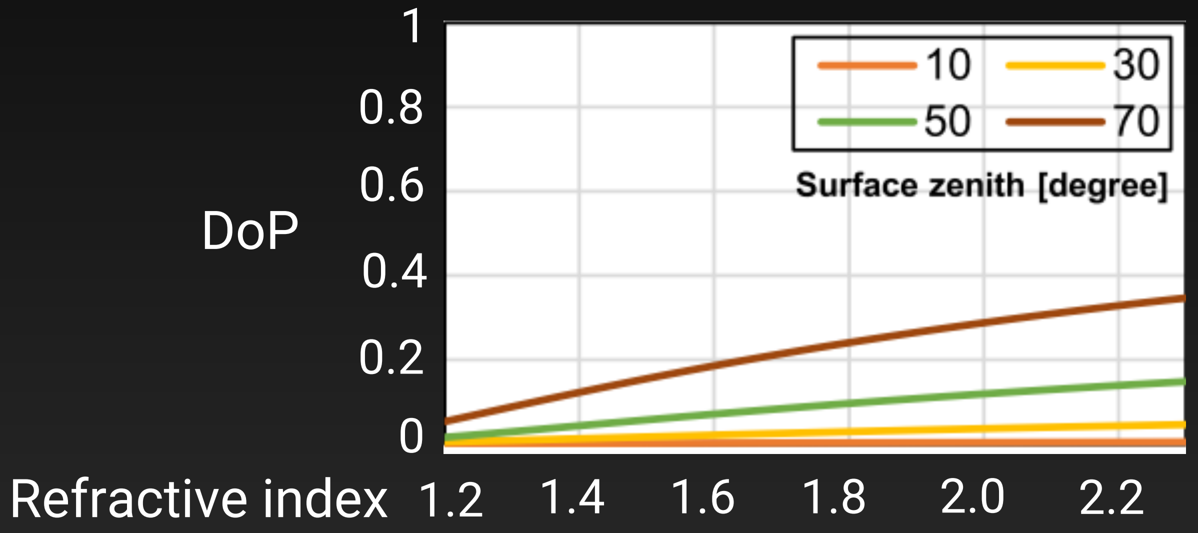
- Refractive index loss function

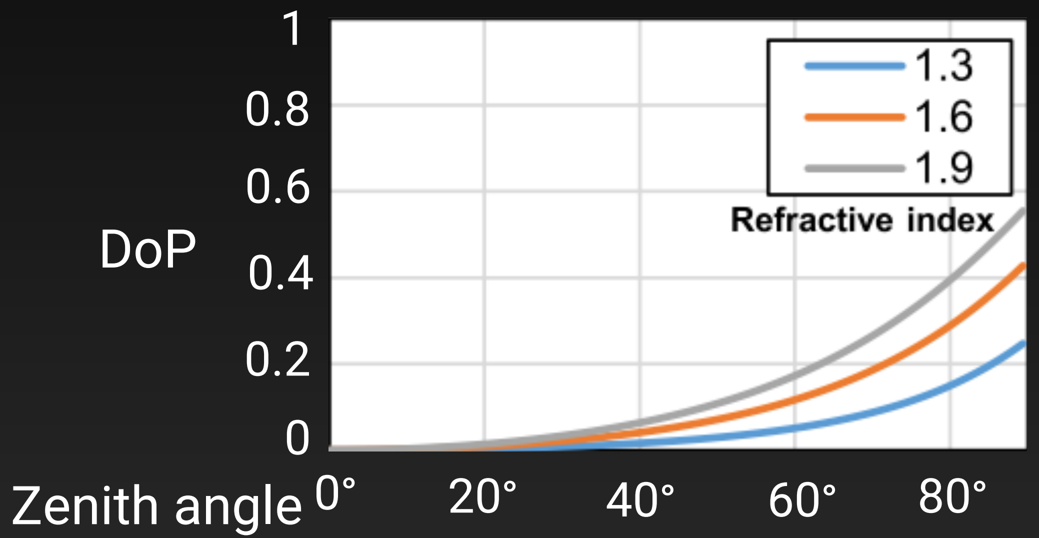
$$L_{\psi} = \sum_{k=1}^{K} w_k^v \left(\hat{\psi}\left(\eta, \theta_{o,k}\right) - \psi_k \right)^2$$

Estimated degree of polarization   Observed degree of polarization

- The degree of polarization (DoP) of the diffuse reflection depends on the **refractive index** and **normal orientation**

[Baek et al. '18]





Diffuse loss

- Comparing the predicted diffuse image with the captured image

$$L_d = \sum_{k=1}^{K} w_k^v \left(\hat{I}_k^d (\mathbf{n}, \rho_d, \eta) - I_k^d \right)^2$$

Estimated diffuse shading   Observed diffuse shading

Specular and single-scattering loss

- We apply a **specular augmentation** strategy with virtual samples

Observed specular and single scattering

Virtual specular and single scattering observation

$$L_s = \sum_{k=1}^{K} w_k^v \left(\hat{I}_k^s - I_k^s \right)^2 + \lambda_g \sum_{m=1}^{M} w_m^a \left(\hat{I}_m^s - \tilde{I}_m^s \right)^2$$

Estimated specular and single scattering

Normal loss

- Azimuth angle information of normal from diffuse polarization

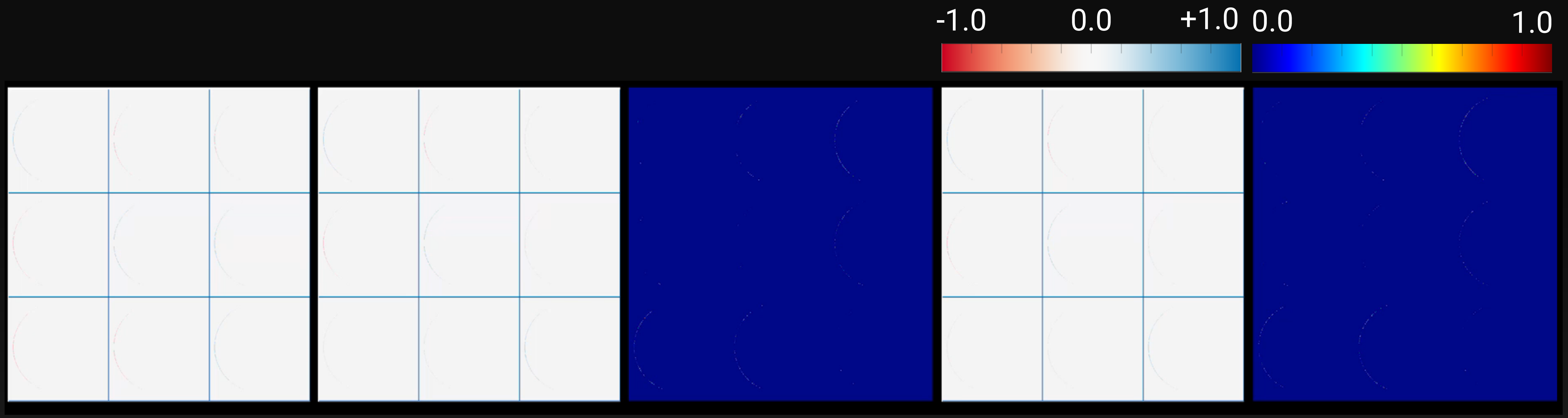
$$L_\phi = \sum_{k=1}^{K} 2w_k^p \left(1 - \cos\left(2\hat{\phi}_{o,k} - 2\phi_{I,k}\right)\right)$$

Azimuth angle of estimated normal Observed azimuth angle from diffuse polarization

Validation

pBRDF model comparison

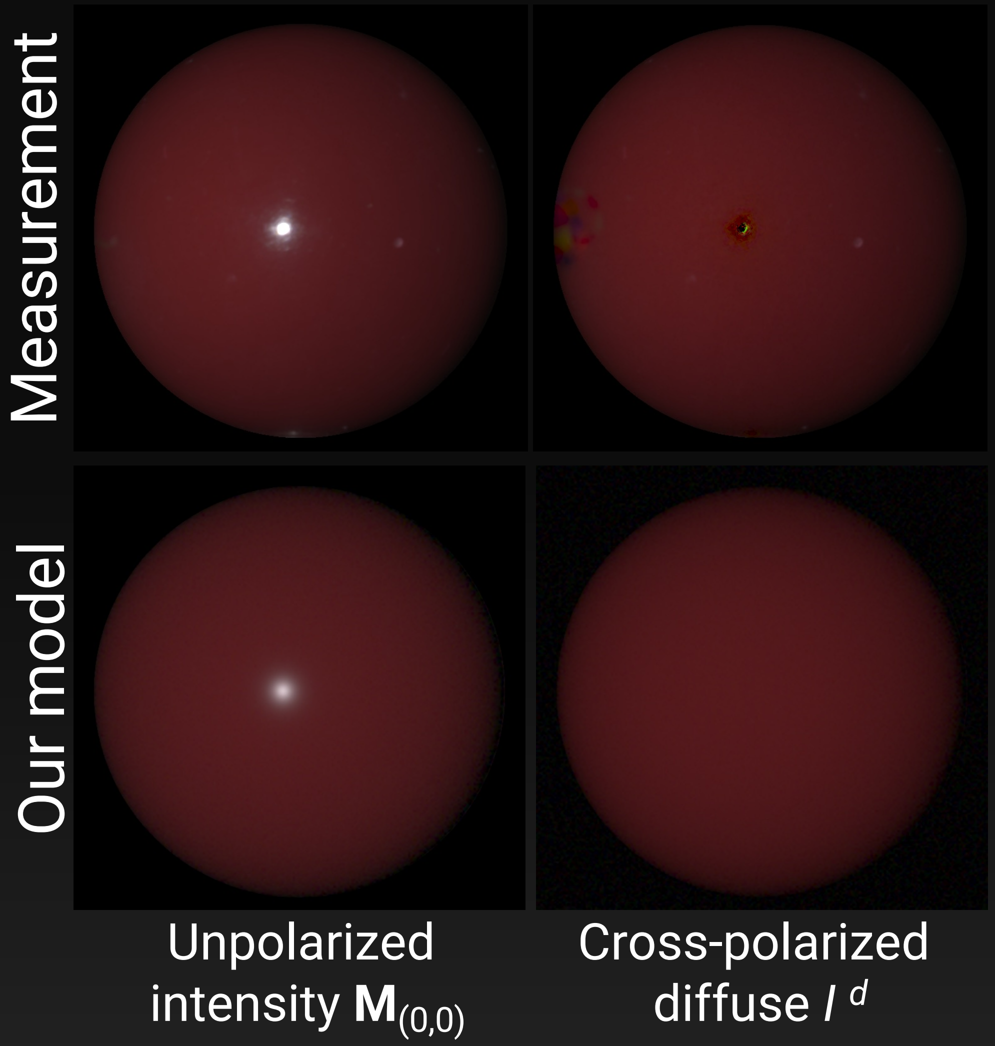
- Comparison between pBRDF measurements and our proposed models



pBRDF Measurement (GT) Full pBRDF model Difference map with GT Practical pBRDF model Difference map with GT

pBRDF measurement dataset: PEEK

Single scattering validation



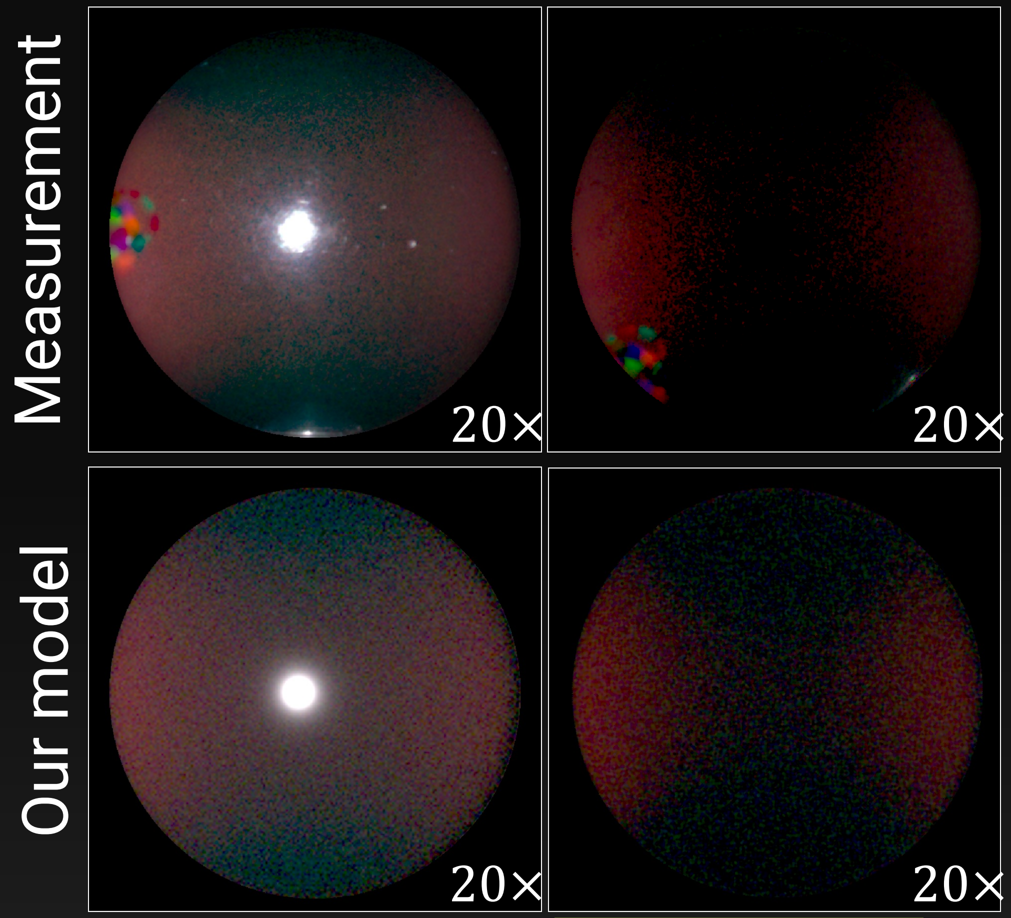
Single scattering validation

Single scattering, specular and diffuse polarization

$$I^{\alpha} = DP\alpha = I_{135} - I_{45}$$

Diffuse polarization

$$I^{s} = SS - DP\beta = I_{0} - I_{90}$$



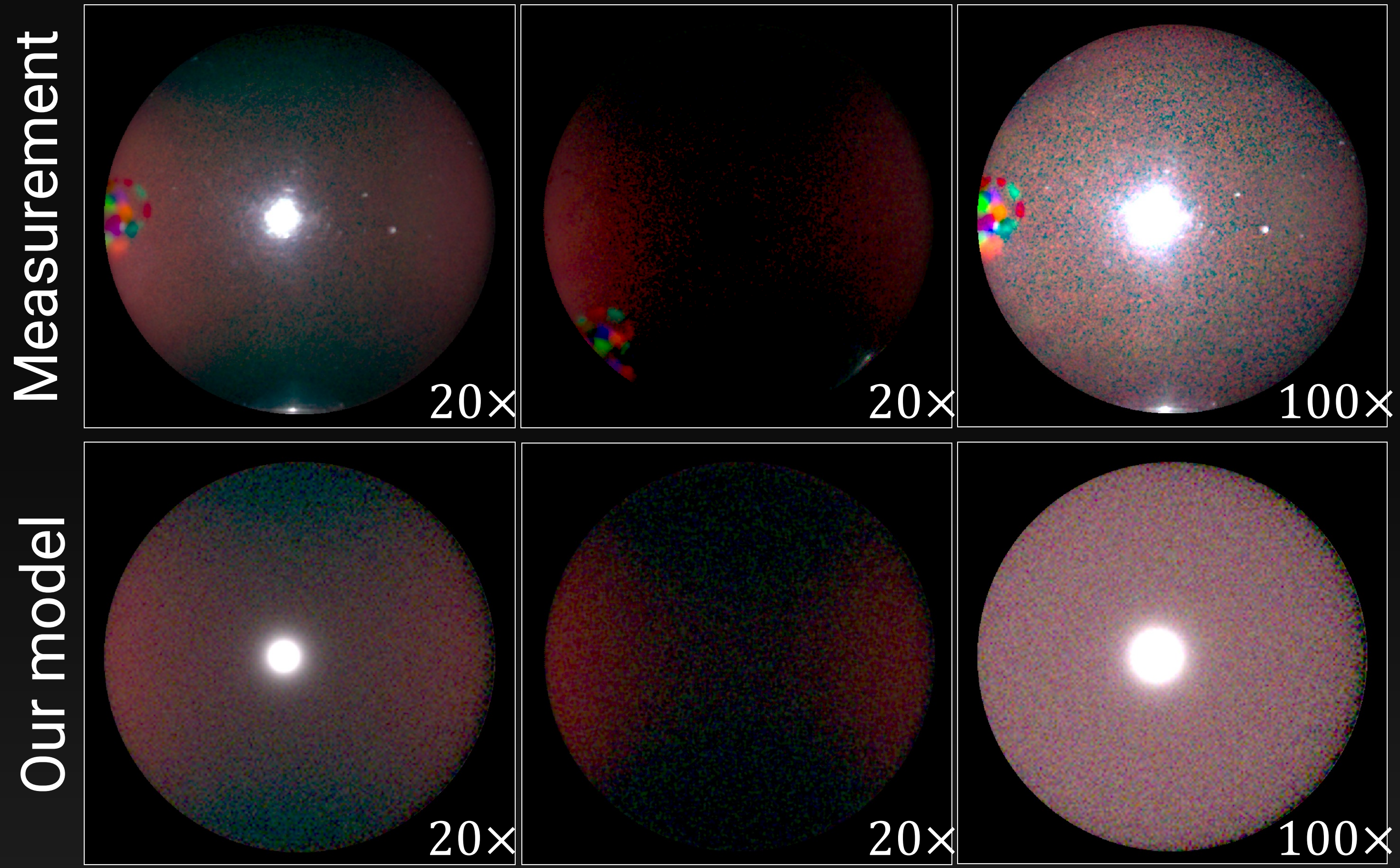
Single scattering, spec., & diff. pol. I^{s}

Rotated diffuse polarization only I^{α}

DS: Diffuse shading component
SS: Specular & single scattering component
$DP\alpha$: Diffuse polarization sine component
$DP\beta$: Diffuse polarization cosine component

Single scattering validation

$$\mathbf{P} \approx \begin{bmatrix} DS+SS & -DP\beta & DP\alpha \\ -DP\beta & SS & 0 \\ -DP\alpha & 0 & -SS \end{bmatrix}$$



Single scattering, spec., & diff. pol. I^s

Rotated diffuse polarization only I^α

Single scattering & specular $\mathbf{P}_{(1,1)}$

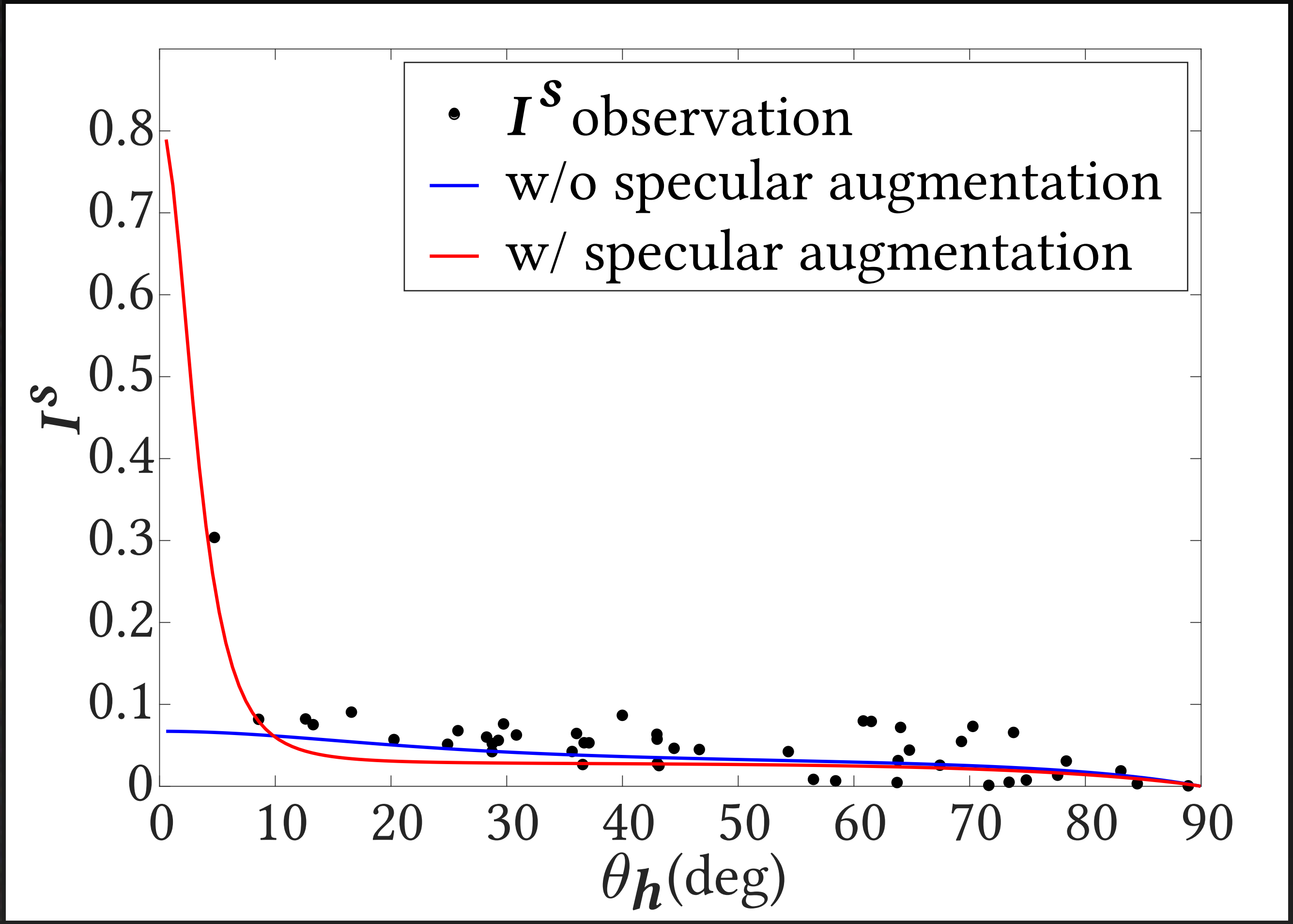
DS: Diffuse shading component
SS: Specular & single scattering component
$DP\alpha$: Diffuse polarization sine component
$DP\beta$: Diffuse polarization cosine component

Refractive index validation

Material	$\eta_{measure}$	η_{ours}	error
White billiard	1.463	1.465	0.10%
Red billiard	1.485	1.476	0.61%
Green billiard	1.503	1.476	1.80%
POM	1.462	1.457	0.34%
Fake pearl	2.295	2.244	2.22%
Yellow silicone	1.303	1.337	2.61%
PEEK	1.663	1.617	2.77%
Average			1.49%

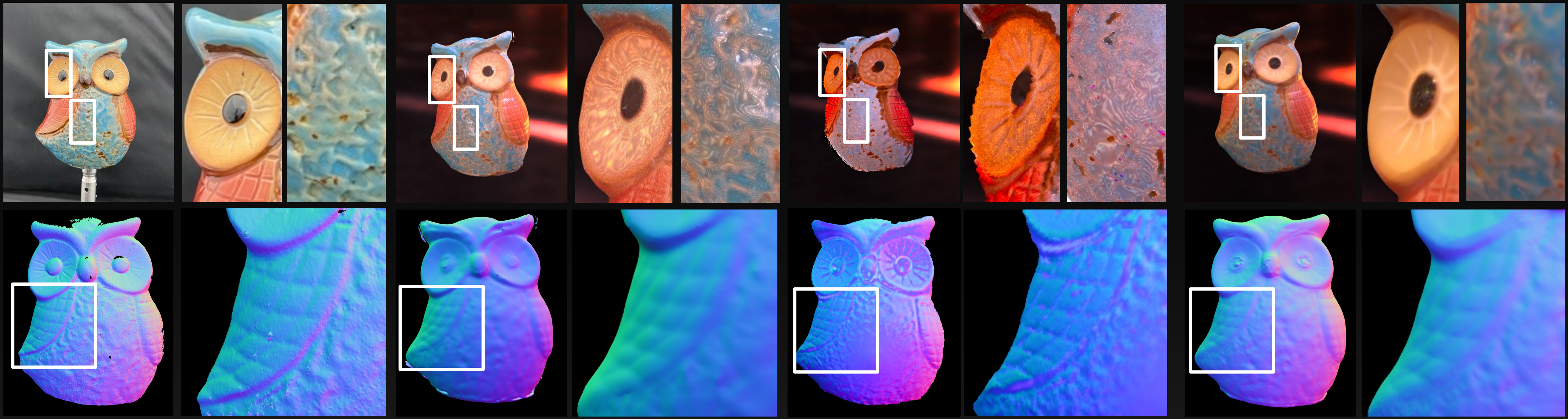
Specular augmentation validation

- Specular observations and fitted specular lobes



Results

Comparison



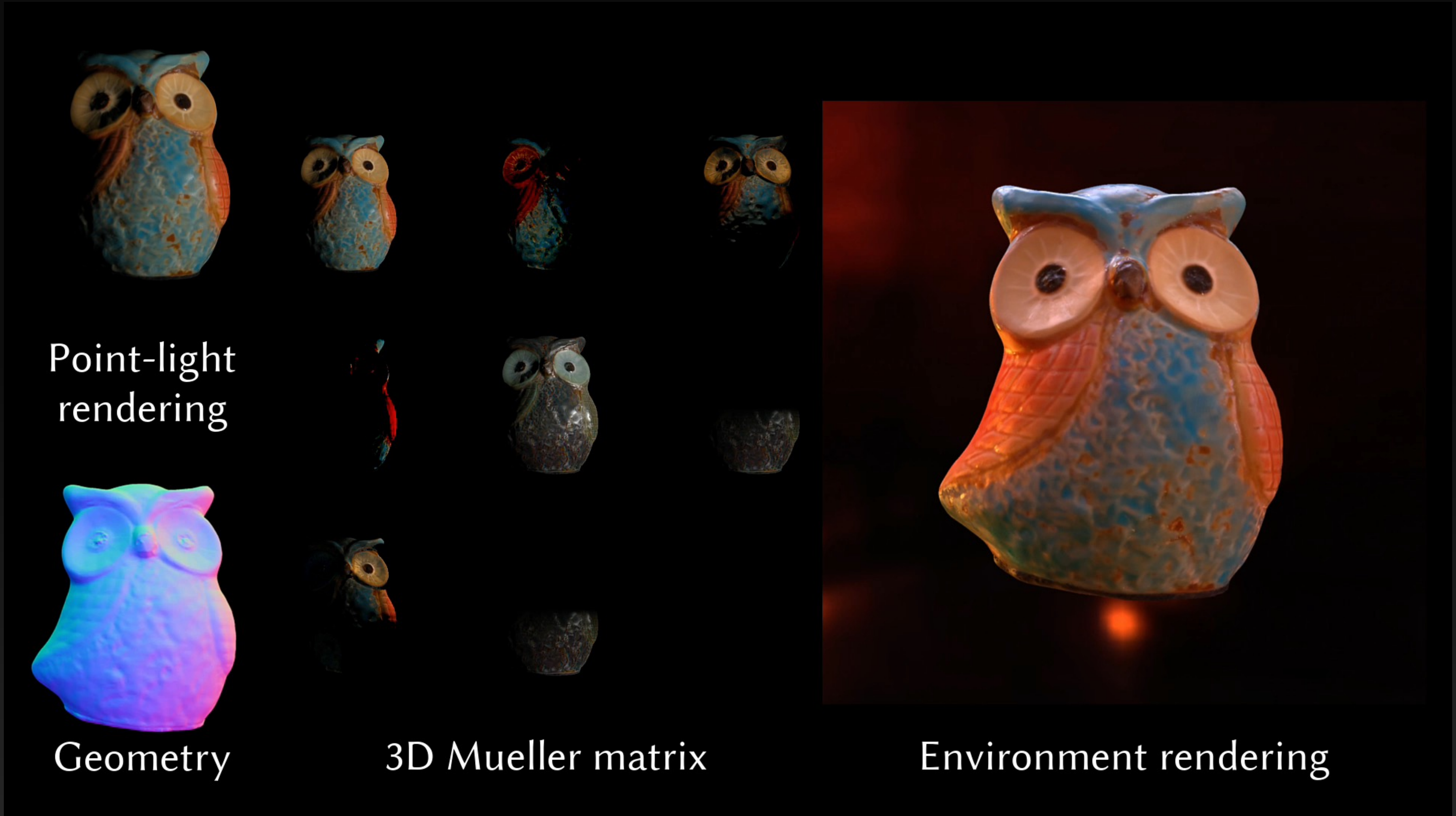
Photograph and scanned geometry

Nam et al. 2018

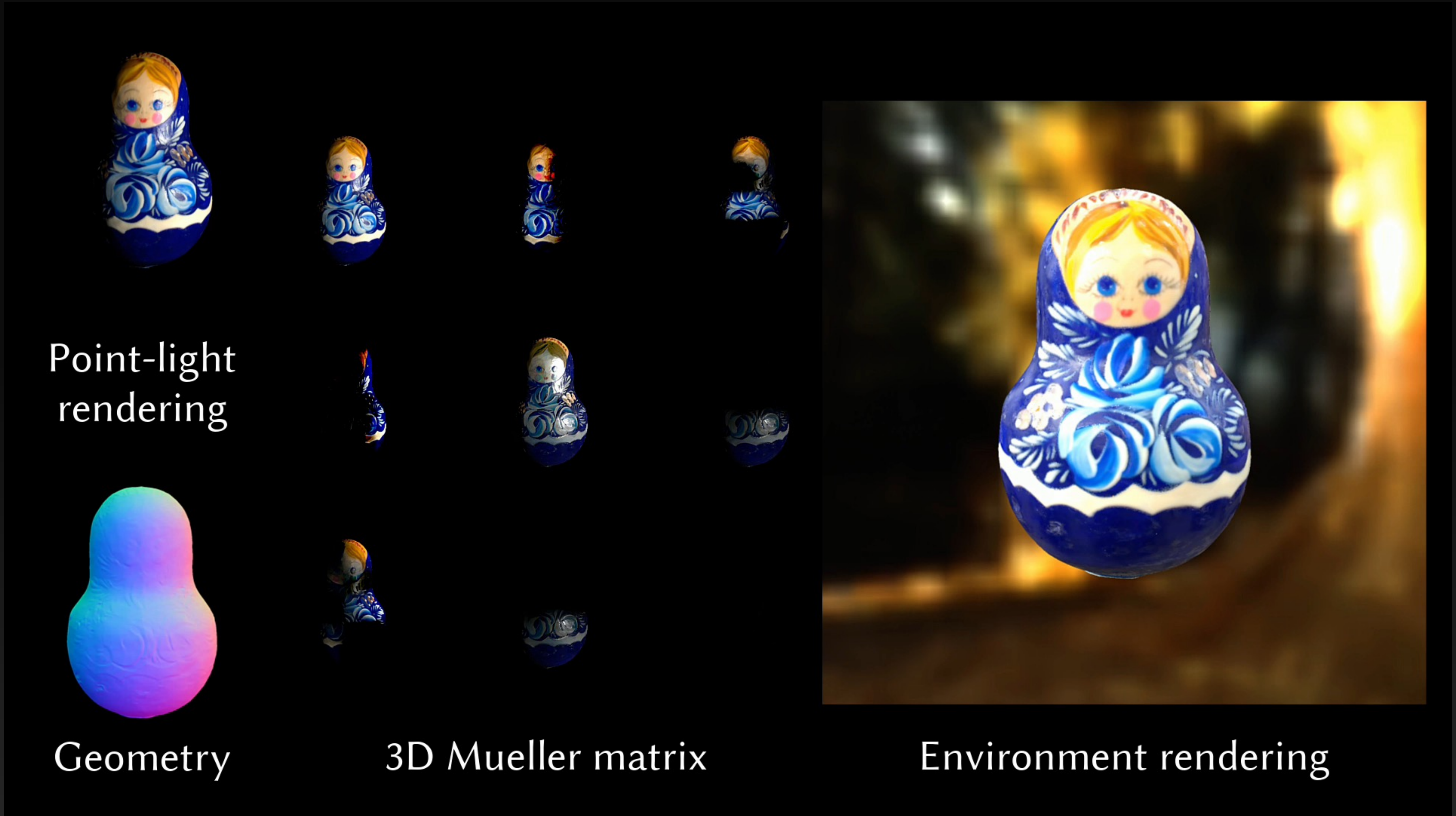
Baek et al. 2018

Ours

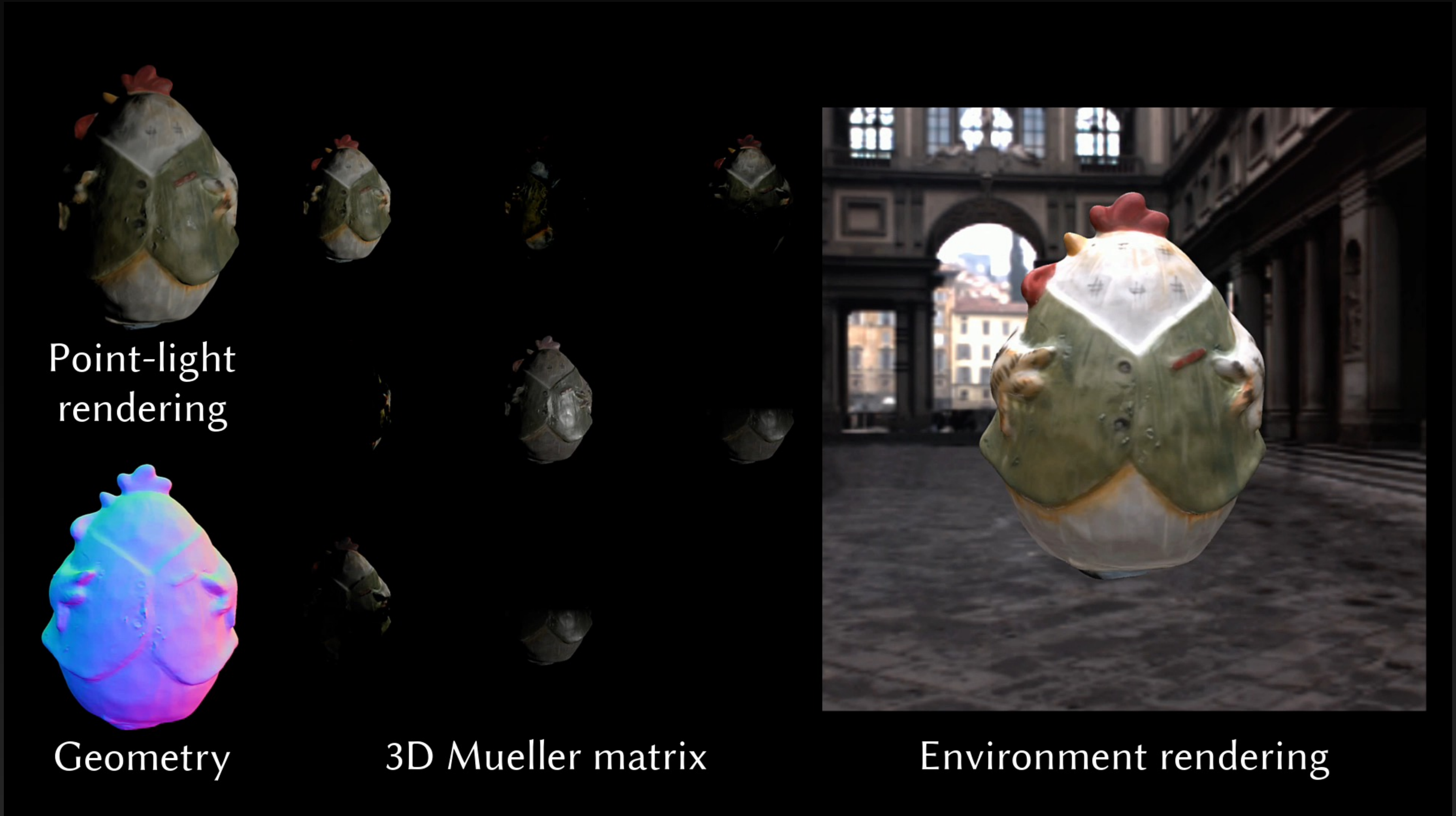
Our results: real-world objects



Our results: real-world objects



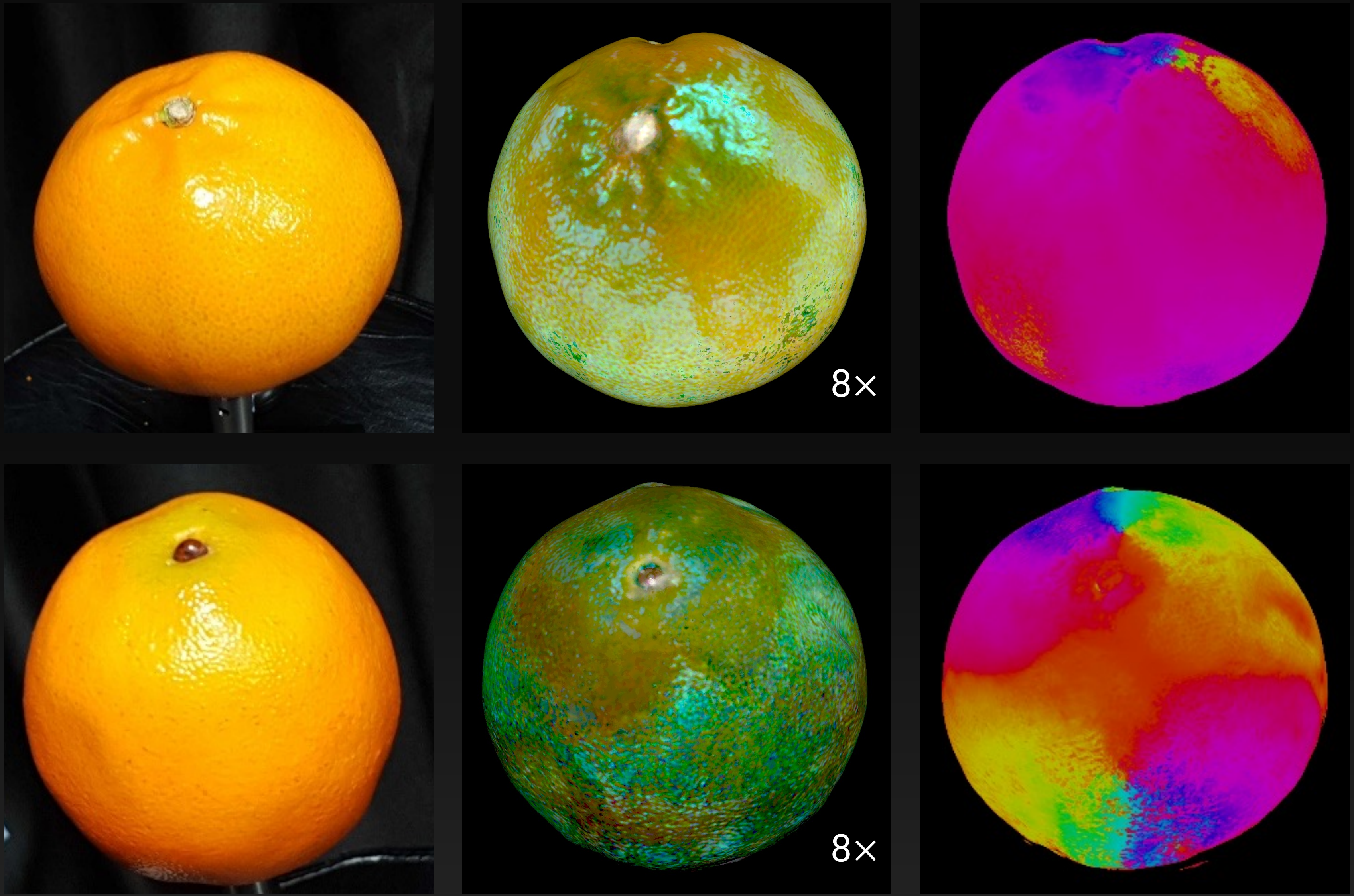
Our results: real-world objects



Single scattering comparison

Real orange

Fake orange



Photographs | Single scattering | AoLP

Discussion

- No circular polarization
- Only for dielectric materials
- Noise in dark surfaces in DoP calculation

Conclusion

- Sparse ellipsometry for 3D objects
  - Estimate both shape and polarimetric BRDF
  - Acquisition takes only a few minutes
- A new pBRDF model
  - Describe diffuse, specular and single scattering
- Project page : http://vclab.kaist.ac.kr/siggraph2022p1/

Thank you

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