Polarimetric Camera Calibration Using an LCD Monitor

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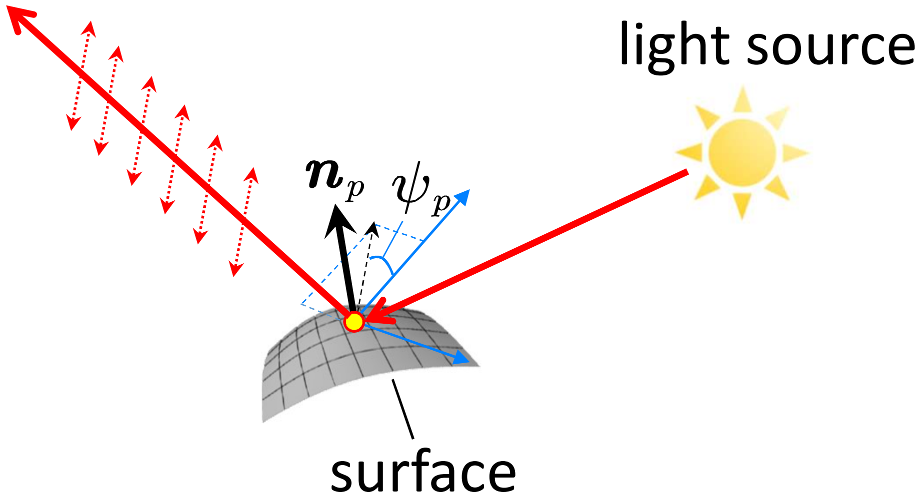
國立臺灣大學 National Taiwan University

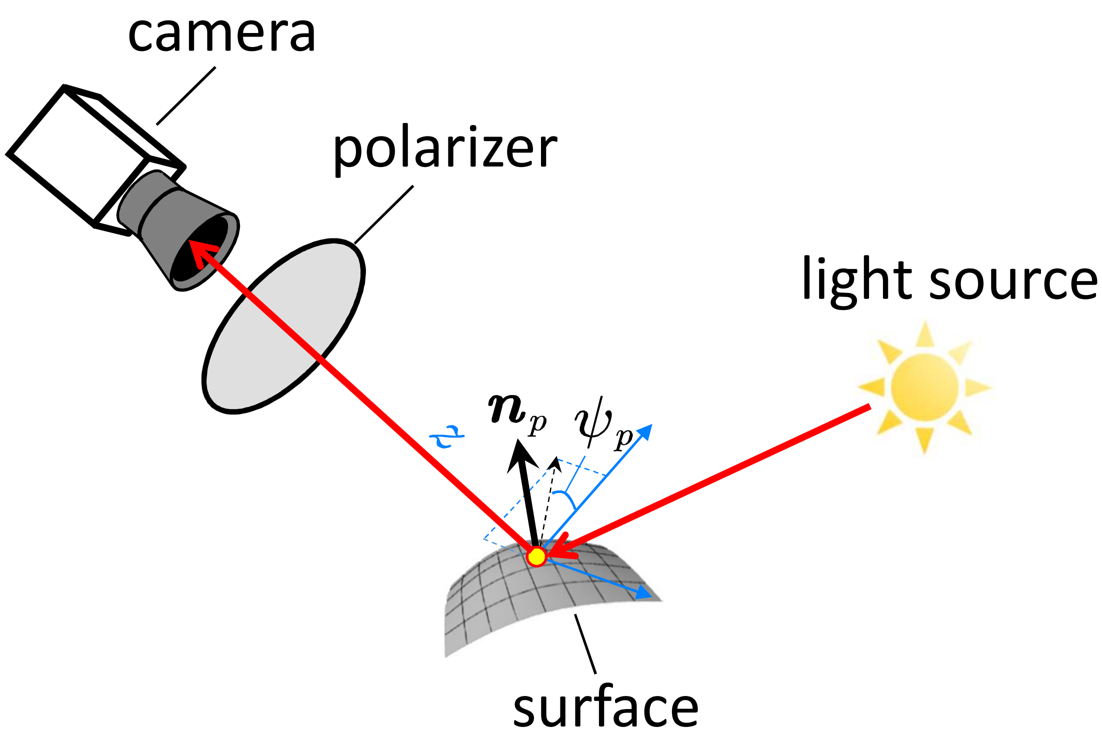
Introduction

Polarization



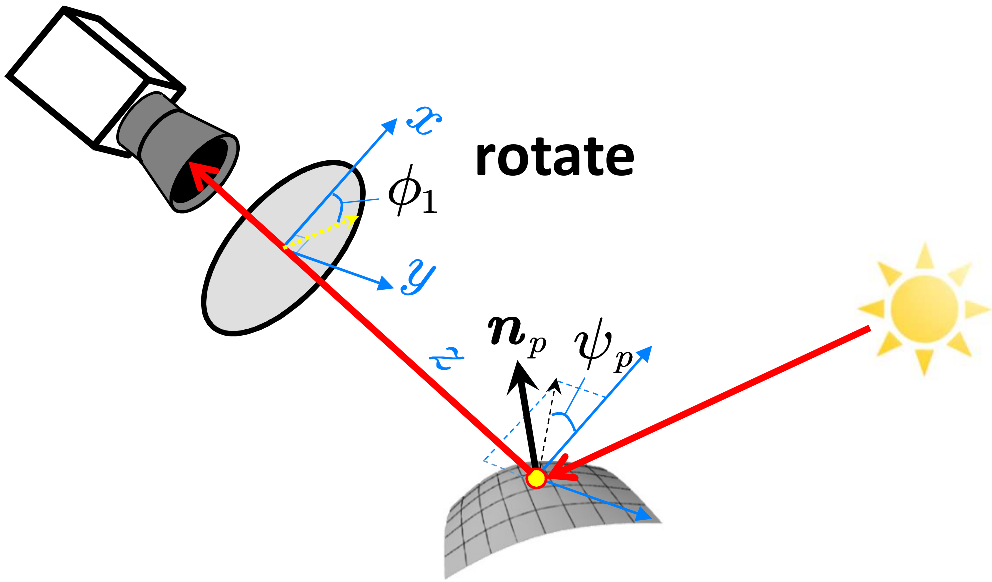
Introduction

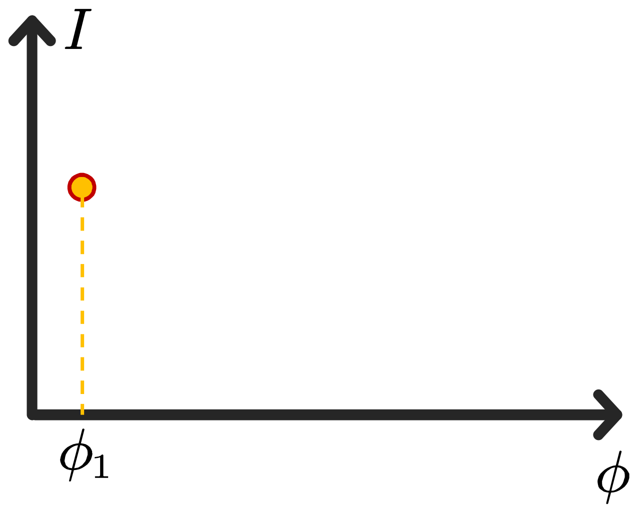
Polarization Imaging



Introduction

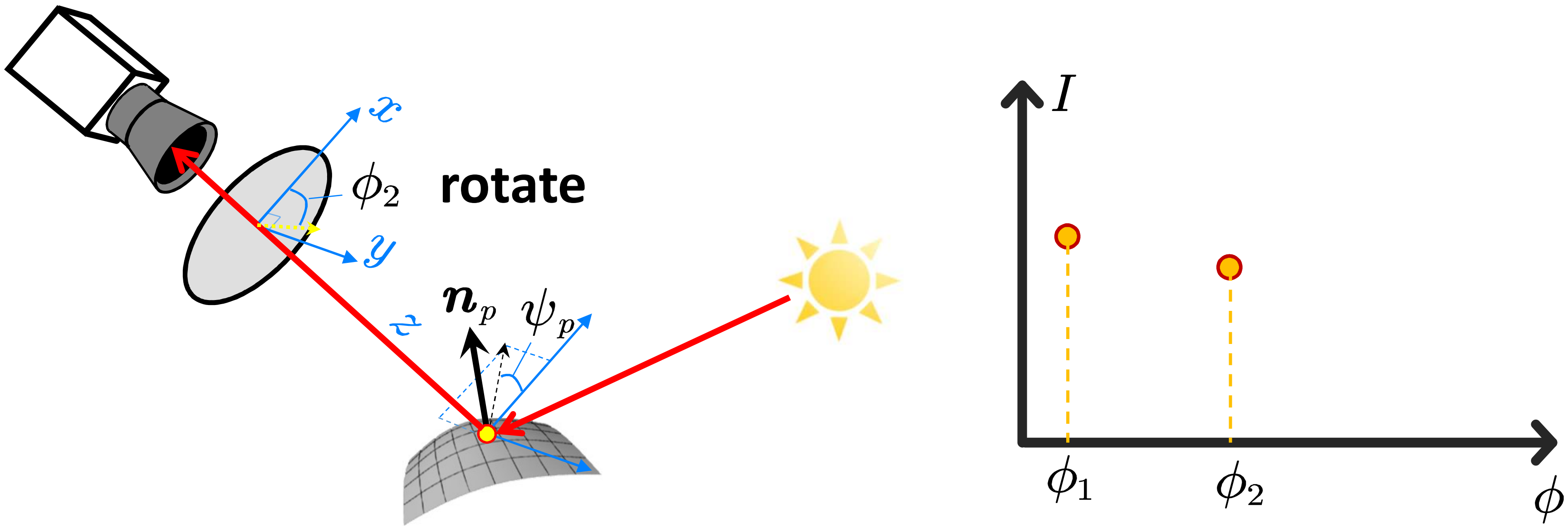
Polarization Imaging





Introduction

Polarization Imaging



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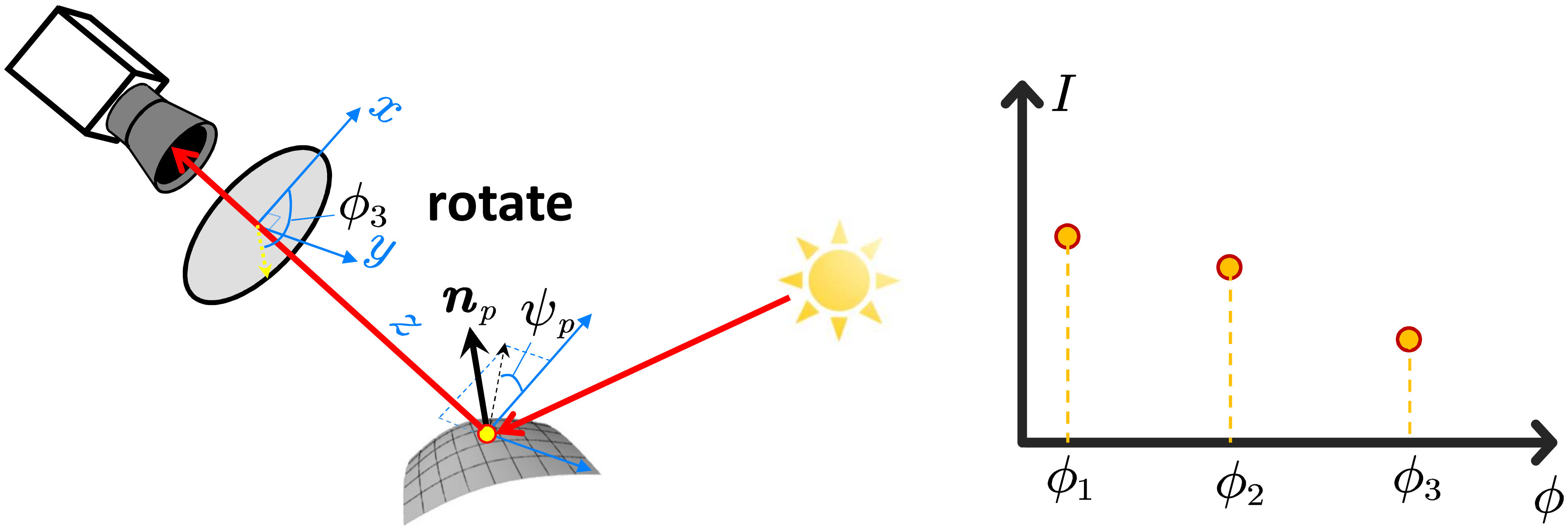
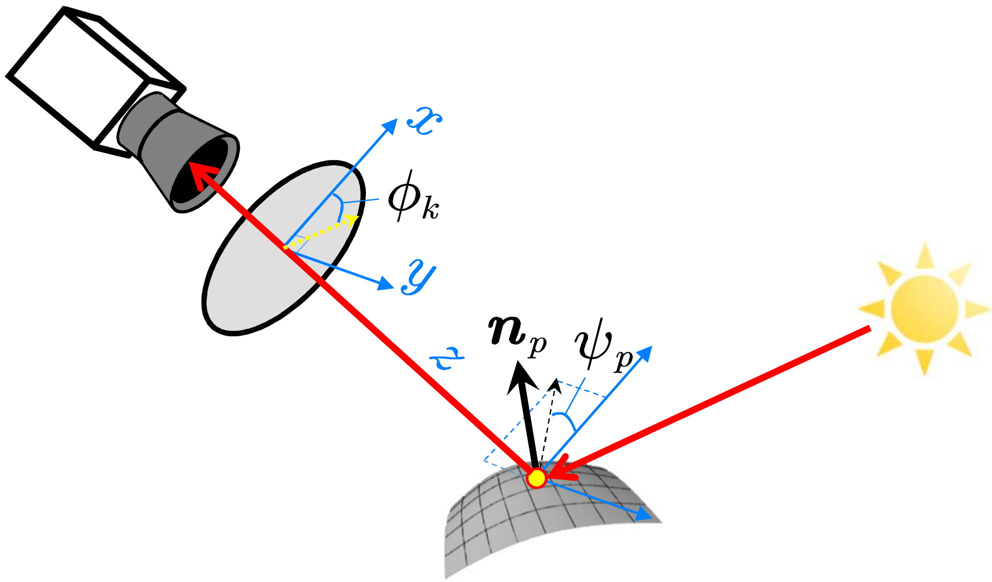
Polarization Imaging

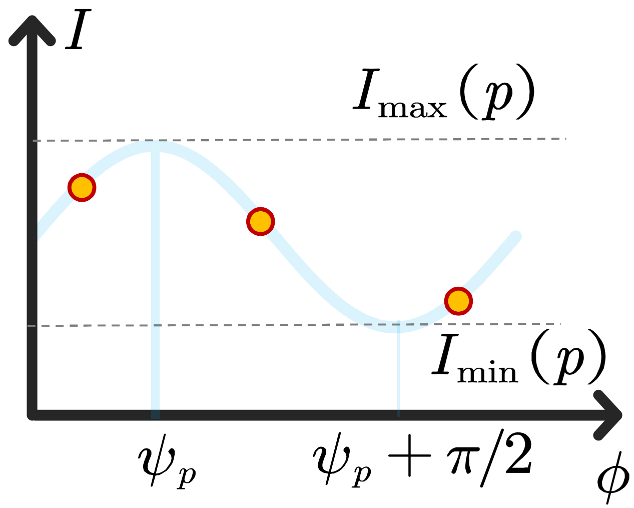


Introduction

Polarization Imaging

$$I_{k,p} = t_p + a_p \cos[2(\phi_k - \psi_p)]$$





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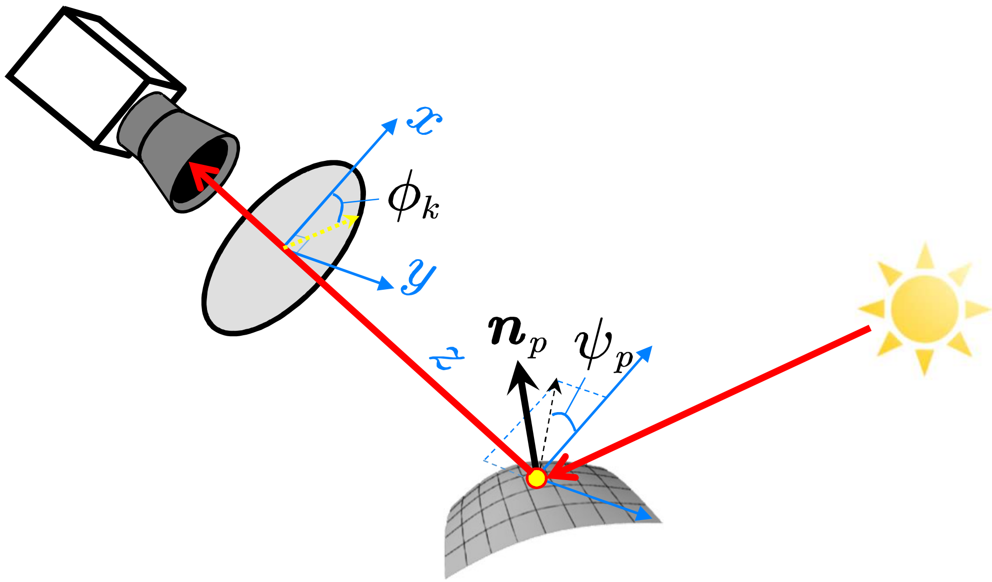
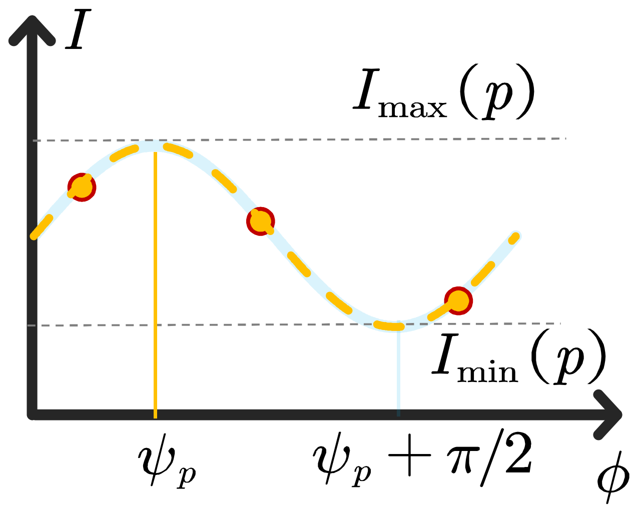


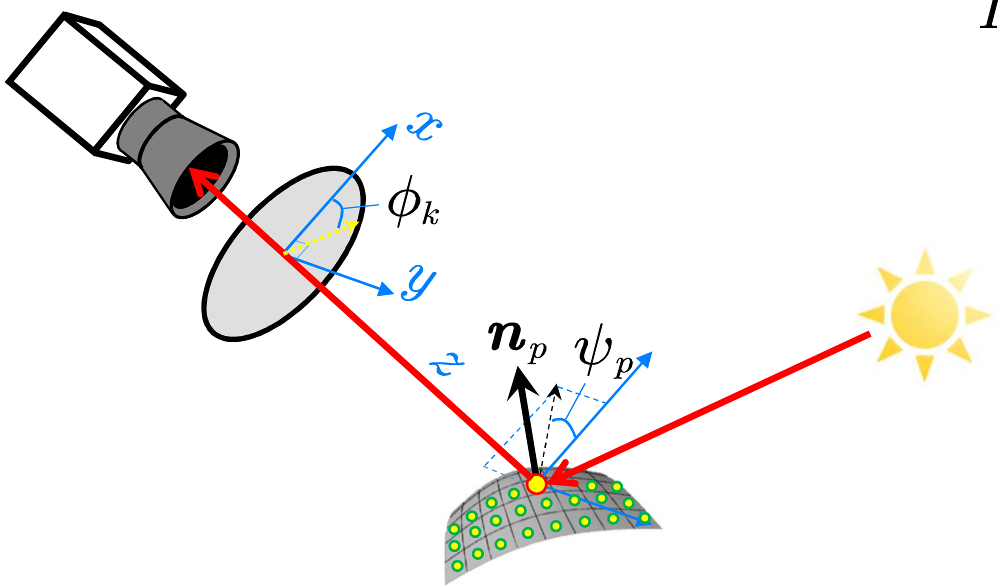


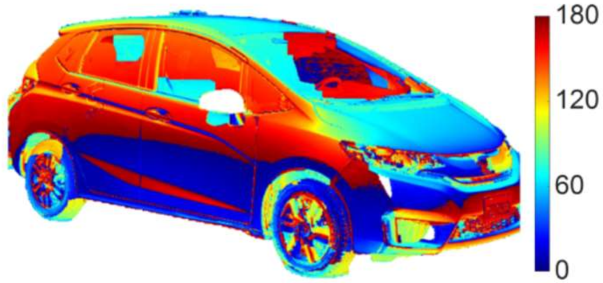
Introduction

Polarization Imaging

Shape from Polarization

$$I_{k,p} = t_p + a_p \cos[2(\phi_k - \boxed{\psi_p})]$$





Estimated Azimuth Angle

[Miyazaki et al. PAMI'04] [Saito et al. CVPR'99]
[Smith et al. ECCV'16] [Yu et al. ICCV'17]

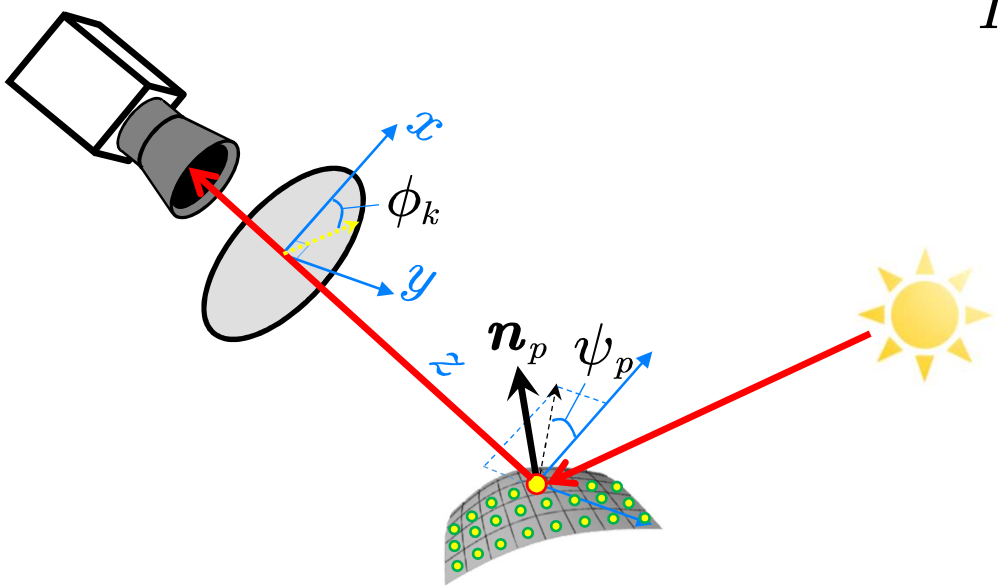
Introduction

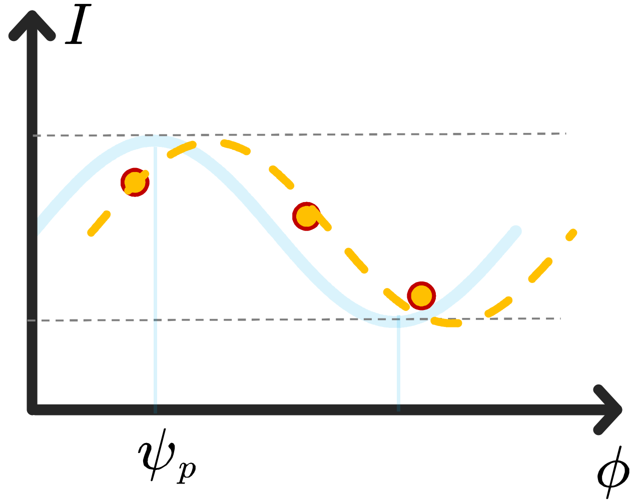
Polarization Imaging

Shape from Polarization

$$I_{k,p} = t_p + a_p \cos[2(\underline{\phi_k} - \boxed{\psi_p})]$$

?





Challenges: - **unknown** polarimetry

Introduction

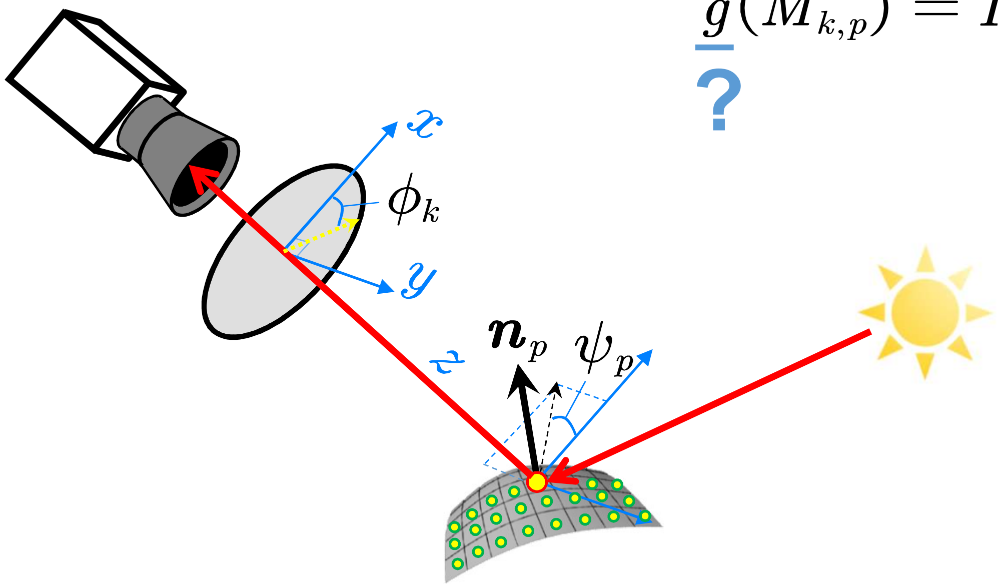
Polarization Imaging

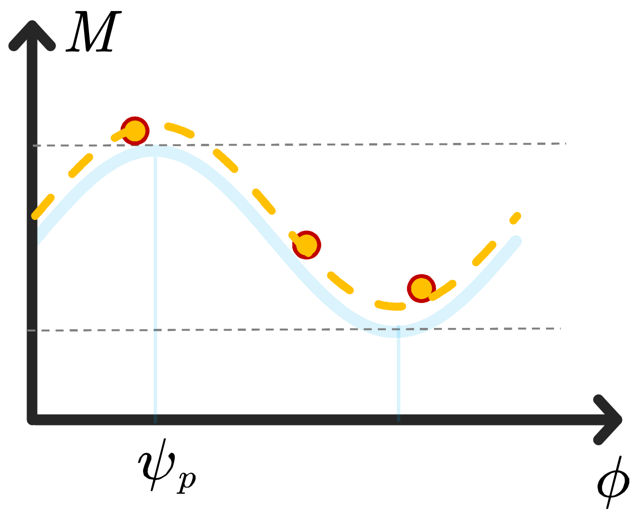
Shape from Polarization

?

$$\underline{g}(M_{k,p}) = I_{k,p} = t_p + a_p \cos[2(\underline{\phi_k} - \boxed{\psi_p})]$$

?





Challenges: - **unknown** polarimetry + radiometry

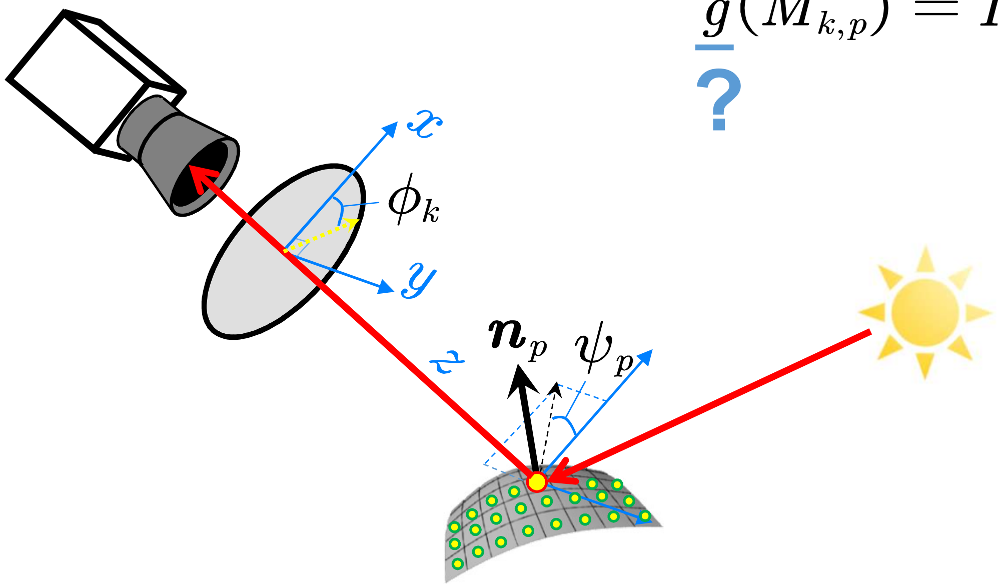
Introduction

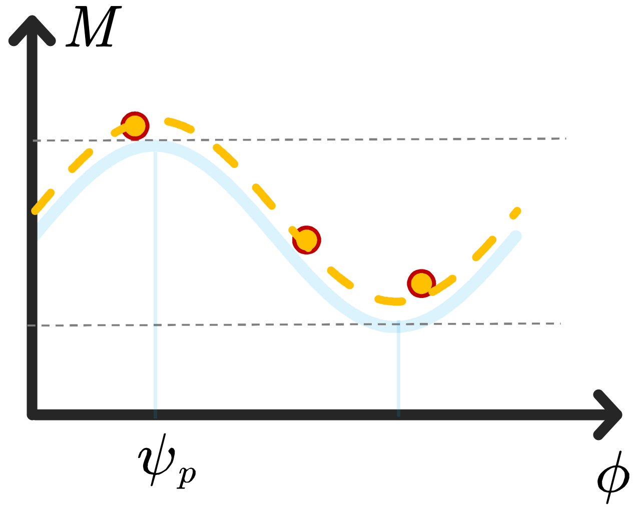
Polarization Imaging

Shape from Polarization

$$g(M_{k,p}) = I_{k,p} = t_p + a_p \cos[2(\phi_k - \boxed{\psi_p})]$$

? ?



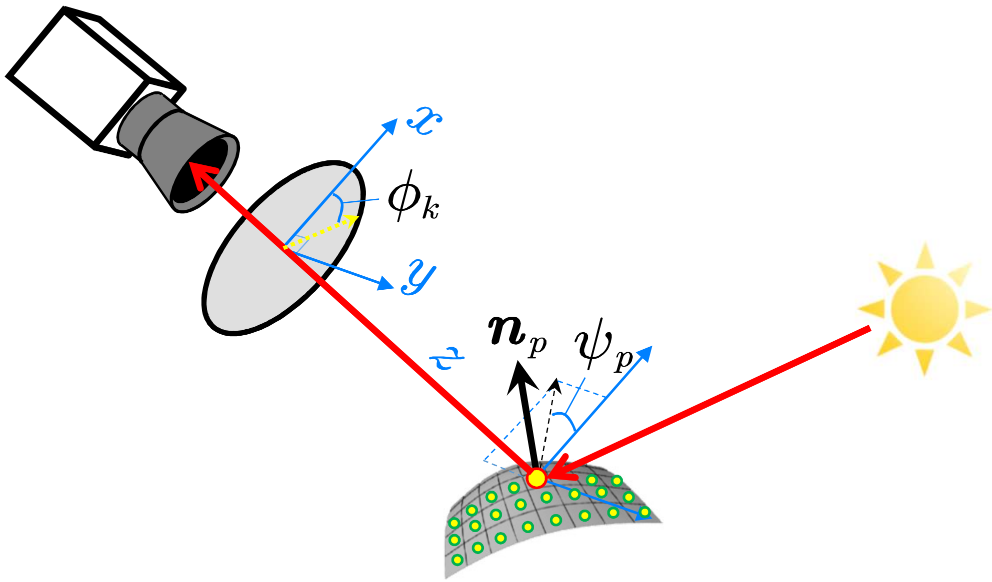


Challenges: - **unknown** polarimetry + radiometry **Calibration**

Introduction

Polarization Imaging

Shape from Polarization



$$\cos\left[2(\phi_k - (\psi_p + \pi))\right]$$

$$=$$

$$\cos\left[2(\phi_k - \psi_p)\right]$$

Challenges: - **unknown** polarimetry + radiometry **Calibration**

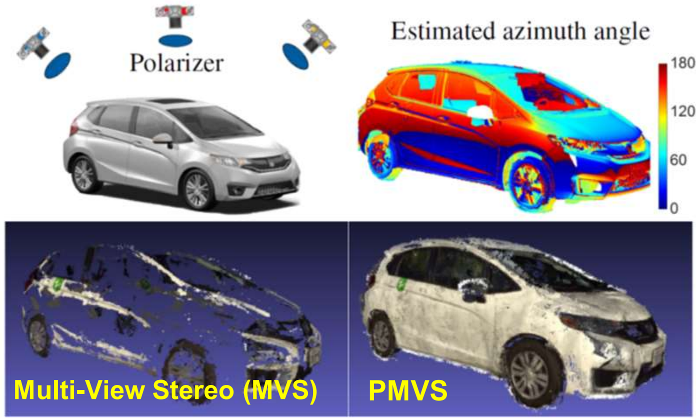
- **ambiguity**

Introduction

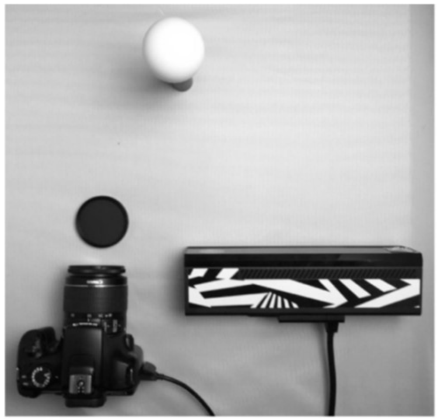
Polarization Imaging

Solve Ambiguity

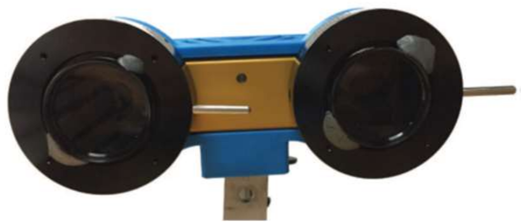
+ Multi-View Stereo + Depth Sensors + Binocular Stereo



[Cui et al. CVPR'17]



[Kadambi et al. IJCV'17]



[Berger et al. ICRA'17]

Challenges: - **unknown** polarimetry + radiometry **Calibration**

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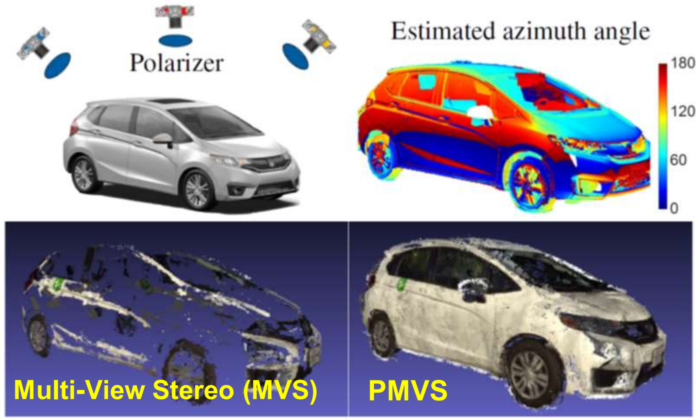
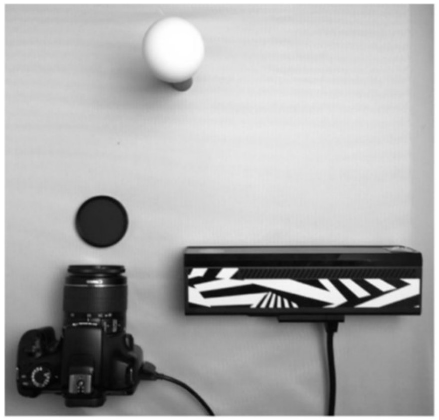
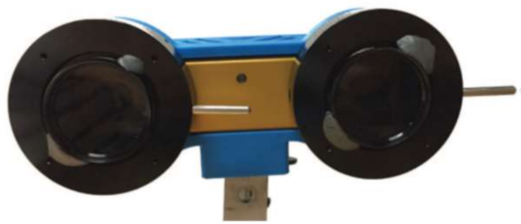
Polarization Imaging

Solve Ambiguity

+ Multi-View Stereo + Depth Sensors + Binocular Stereo







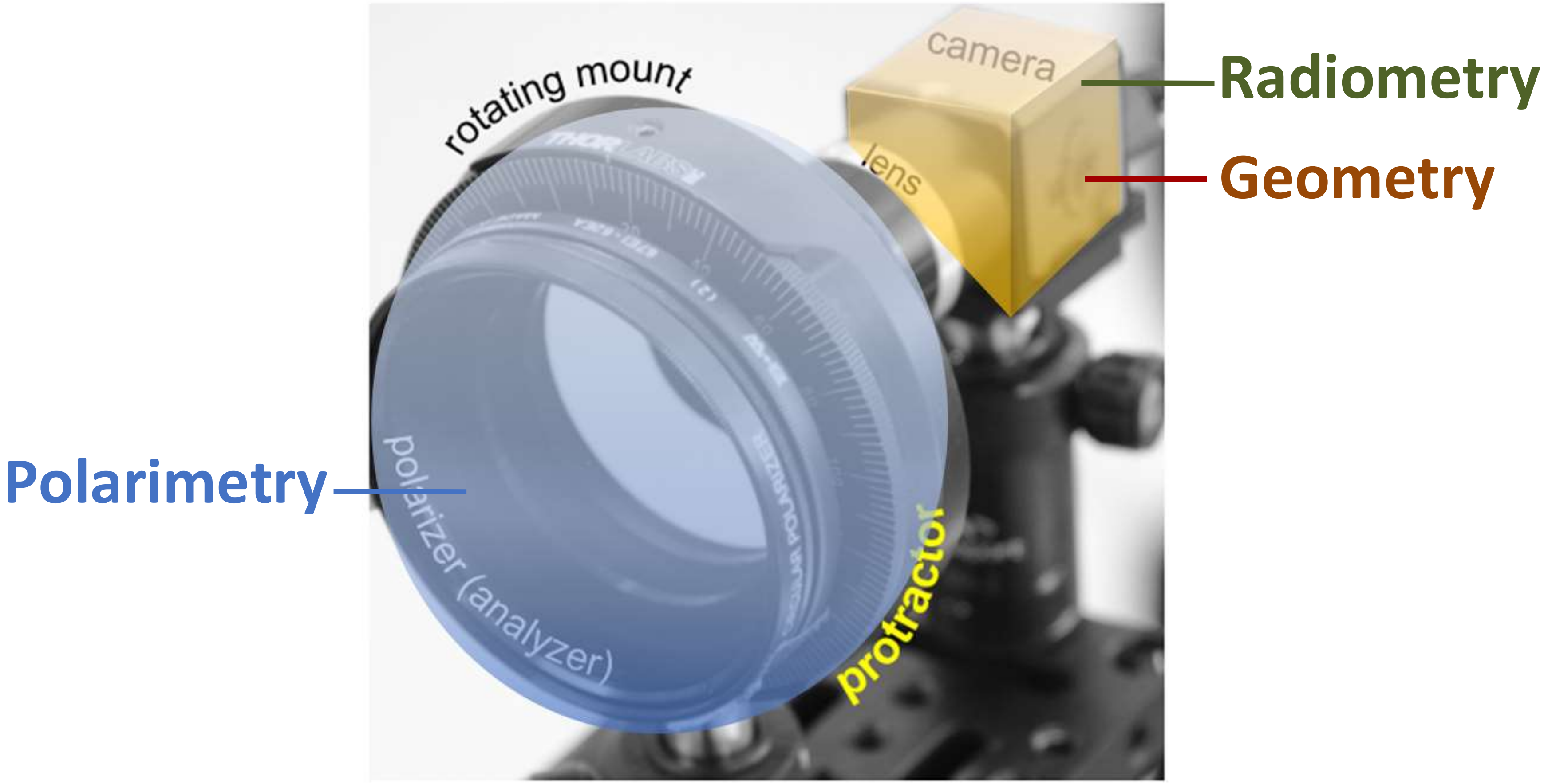
[Cui et al. CVPR'17] [Kadambi et al. IJCV'17] [Berger et al. ICRA'17]

Challenges: - **unknown** polarimetry + radiometry
- require extra geometric parameters

Calibration

Introduction

Goal: Calibrate a polarimetric camera



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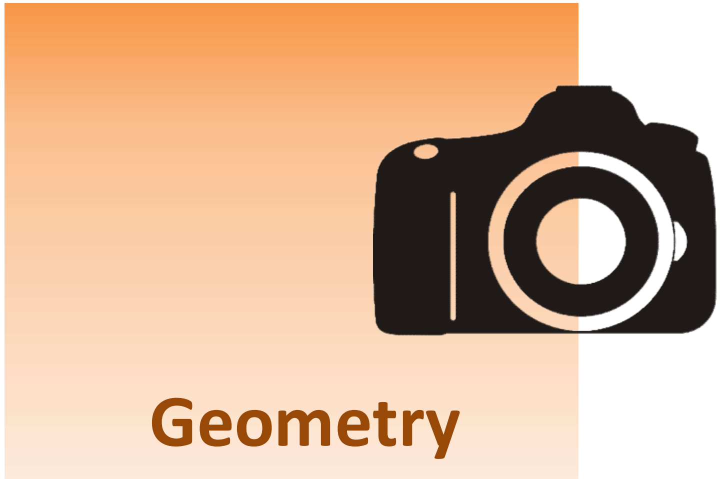

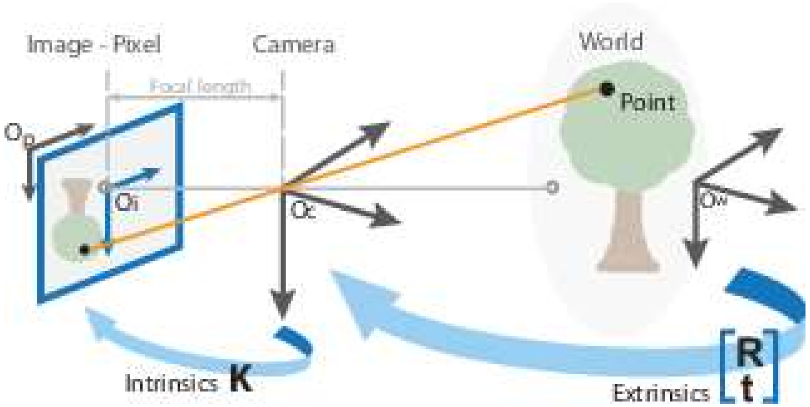

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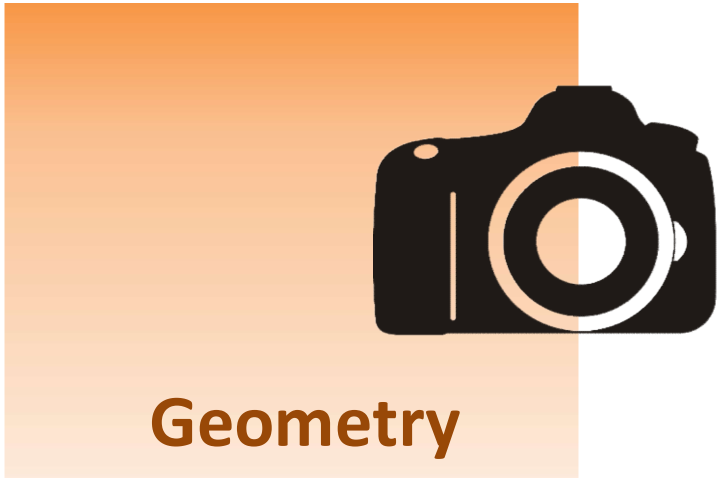
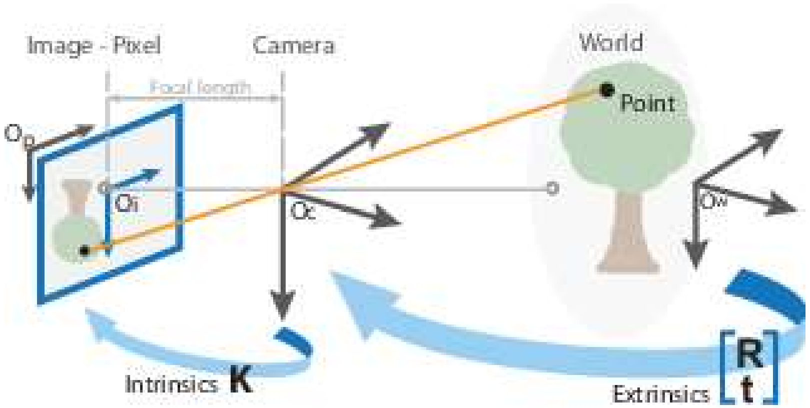
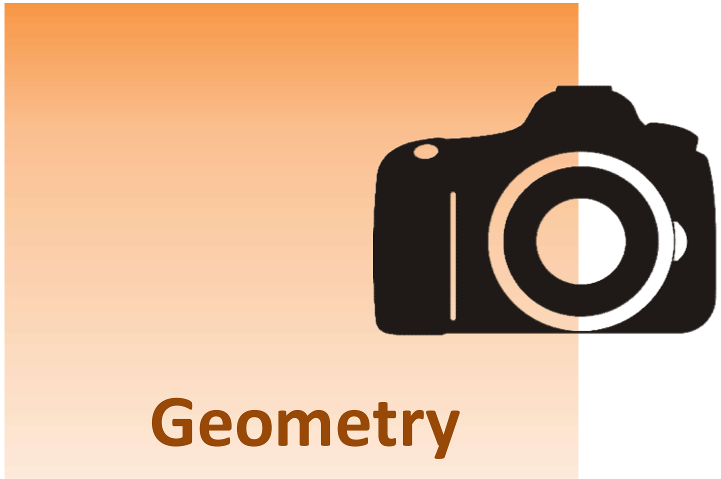


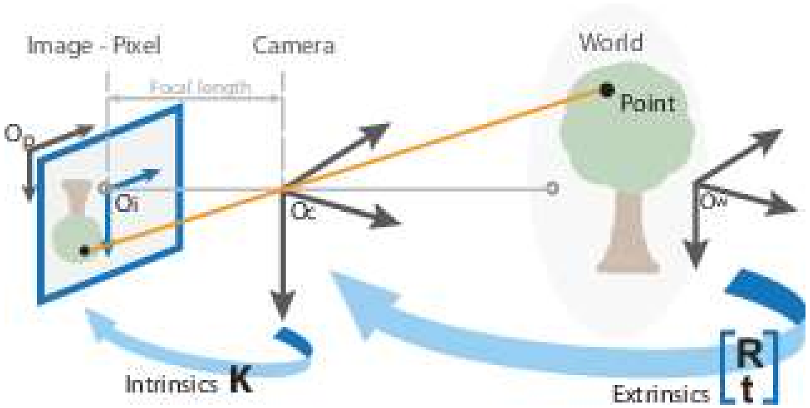


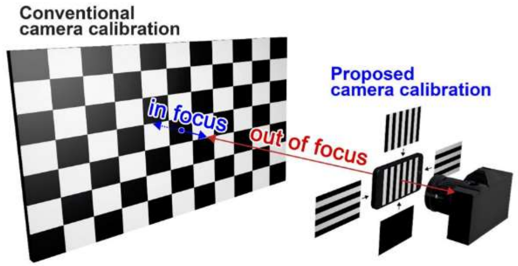
[Zhang et al. PAMI’00]

Introduction

Goal: Calibrate a polarimetric camera







[Ha et al. ICCV’15]

Introduction

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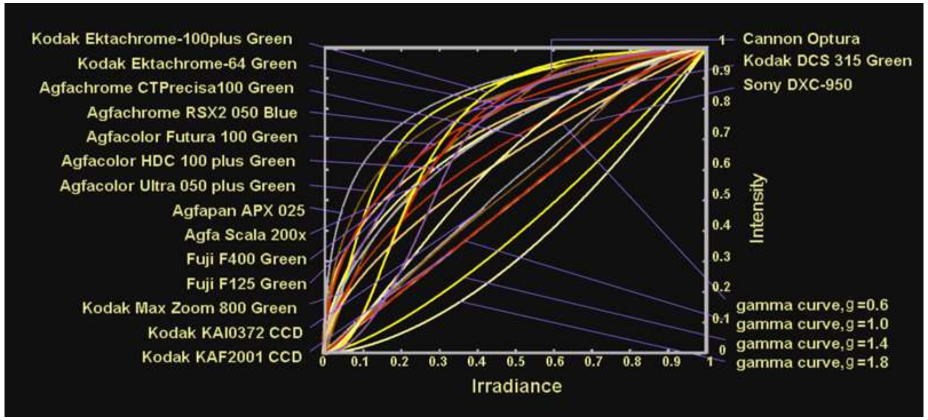
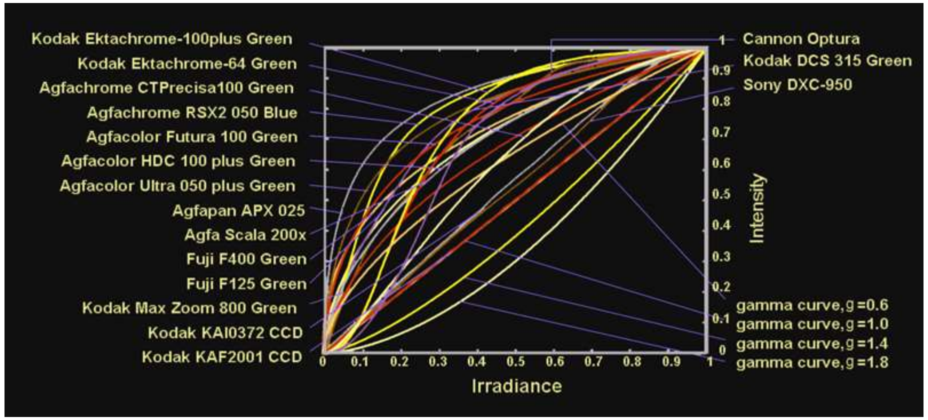


Introduction

Goal: Calibrate a polarimetric camera

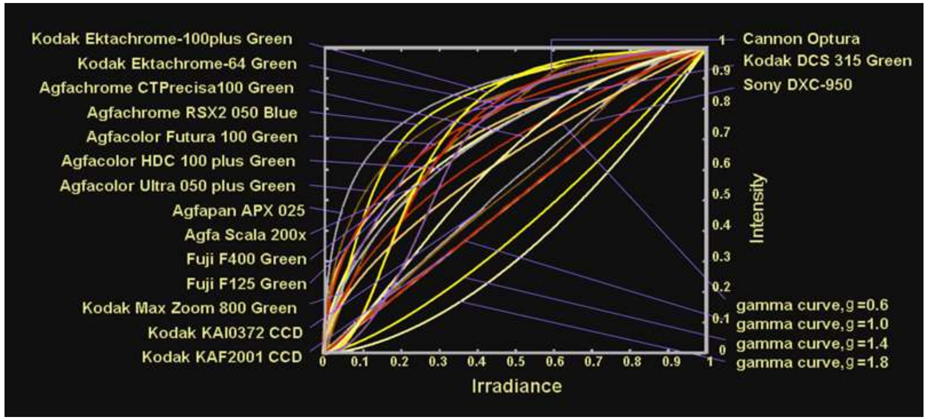
Radiometry

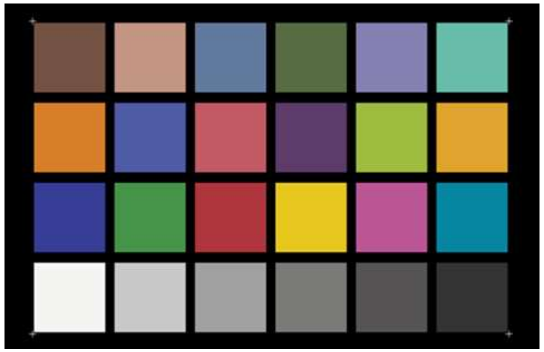


[Debevec et al. Siggraph'97]

Introduction

Goal: Calibrate a polarimetric camera





[McCamy et al. 76]

Introduction

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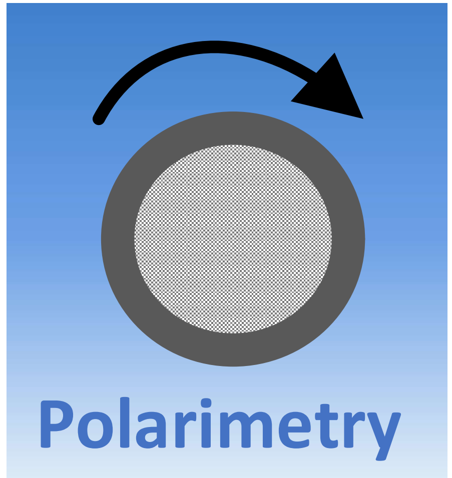
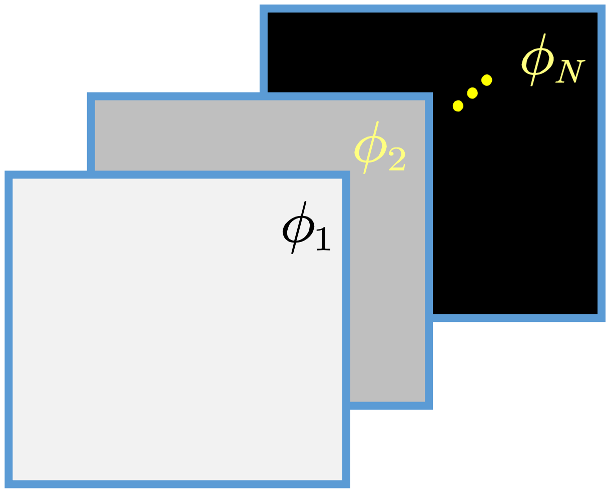


$$I_{k,p} = t_p + a_p \cos[2(\boxed{\phi_k} - \psi_p)]$$



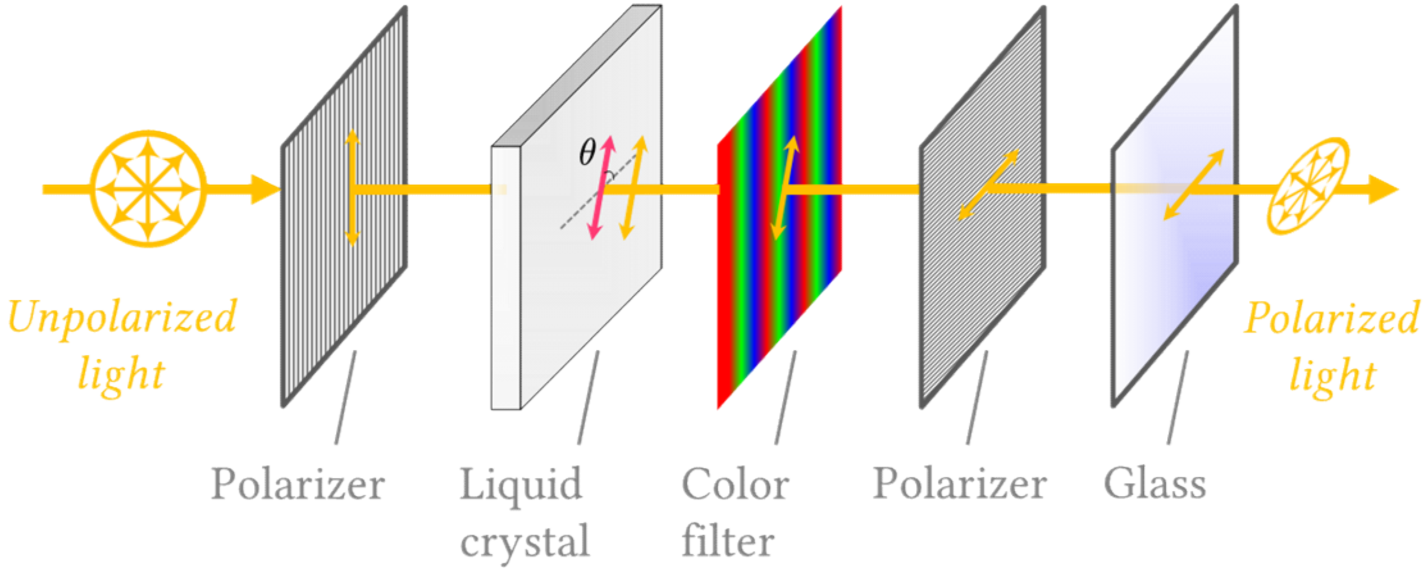
Introduction

Main idea: Using an LCD monitor

Introduction

Main idea: Using an LCD monitor

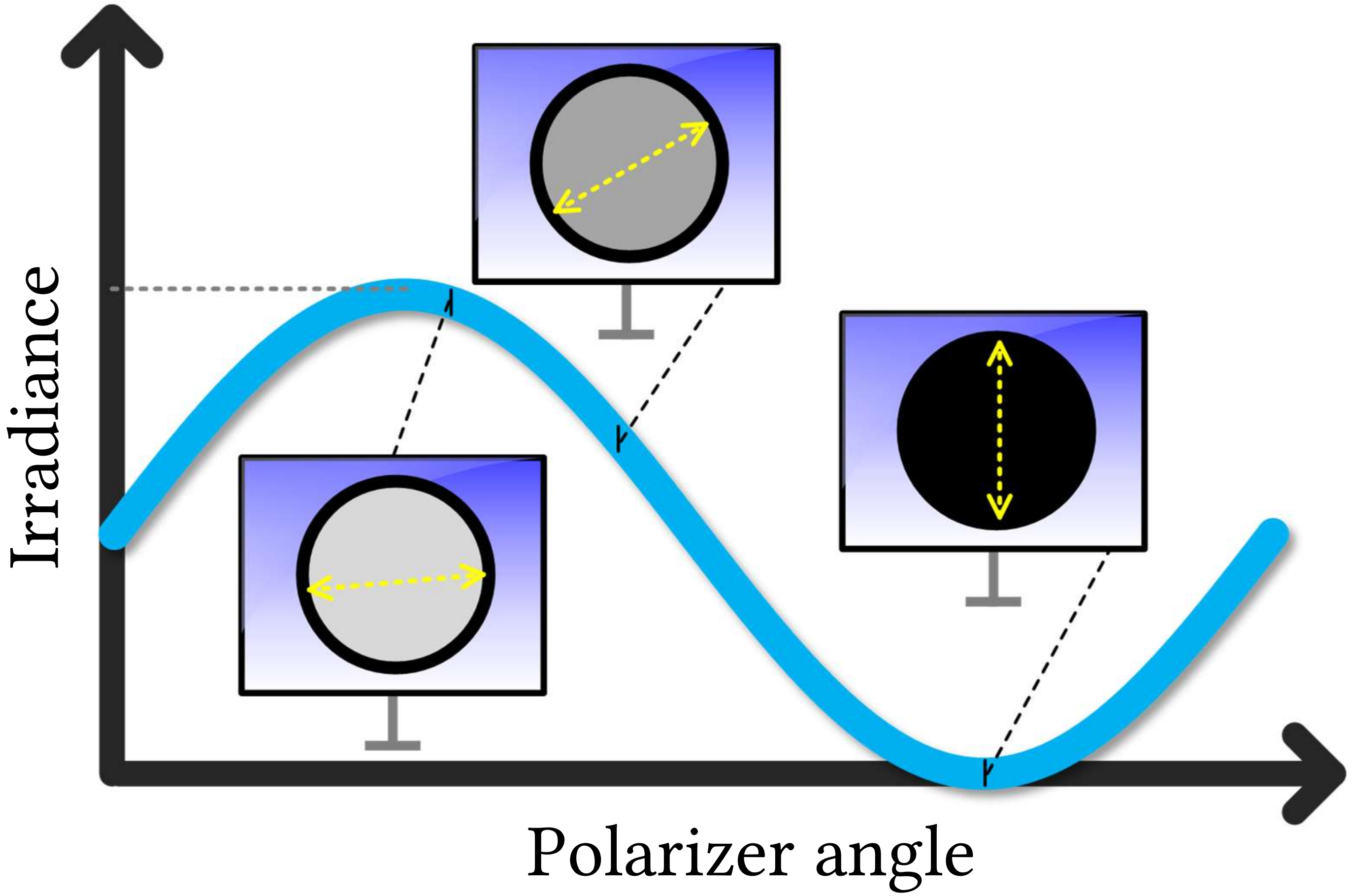
Typical interior structure of LCD monitors



Introduction – Motivation

LCD monitors

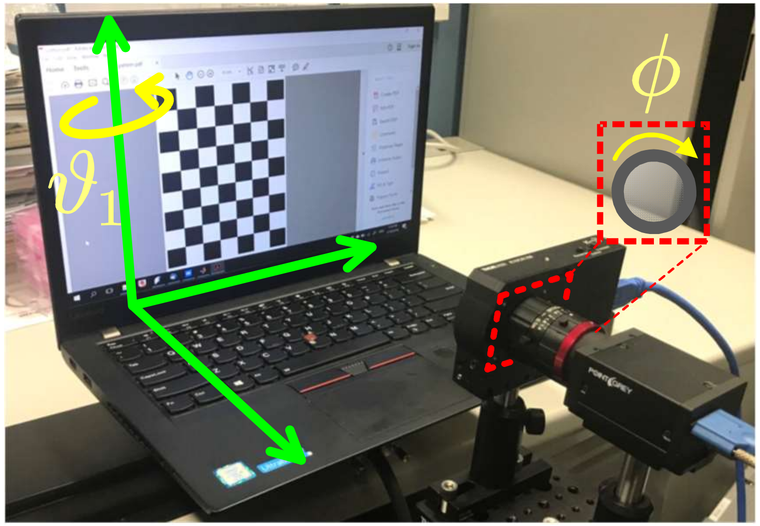
Viewed by a polarimetric camera

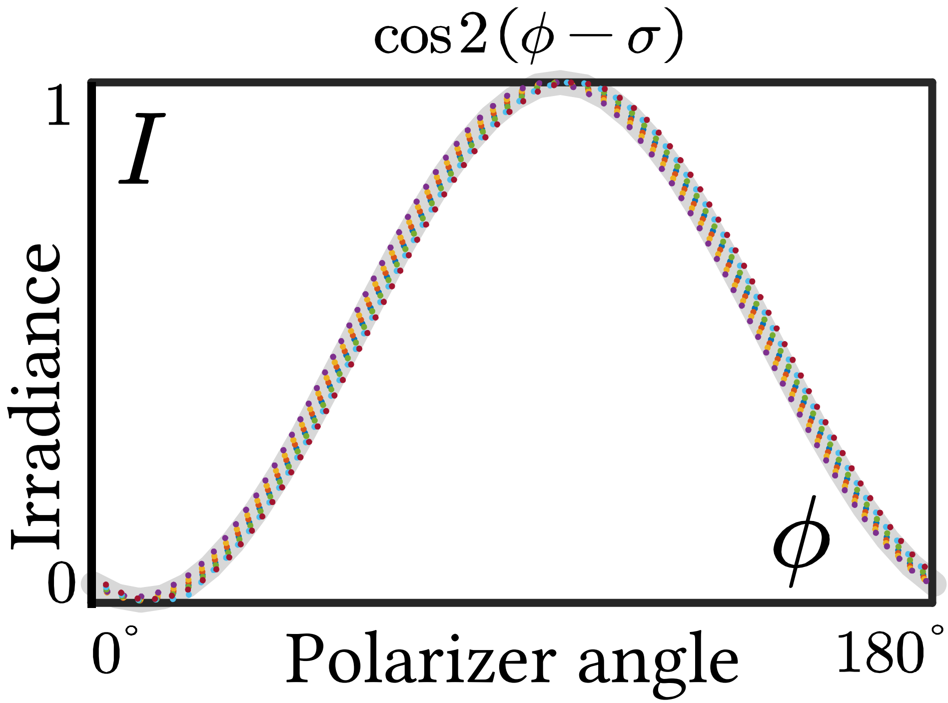


Introduction – Motivation

LCD monitors

Characteristics A. In-plane rotation





Introduction – Motivation

LCD monitors

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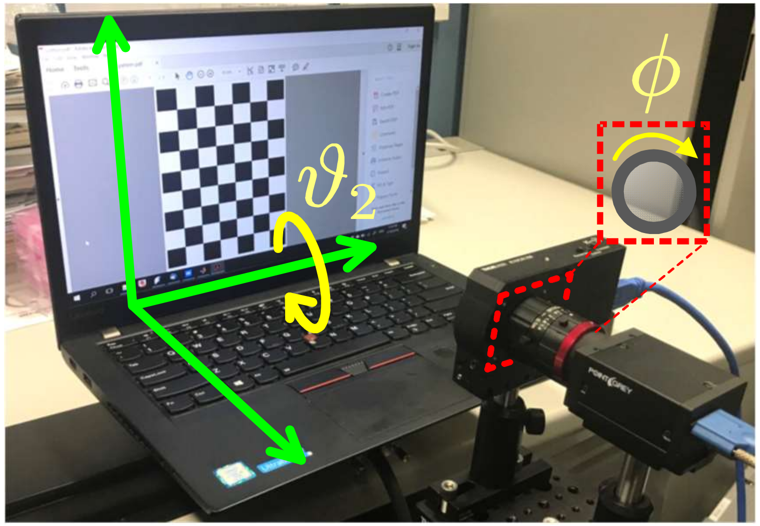

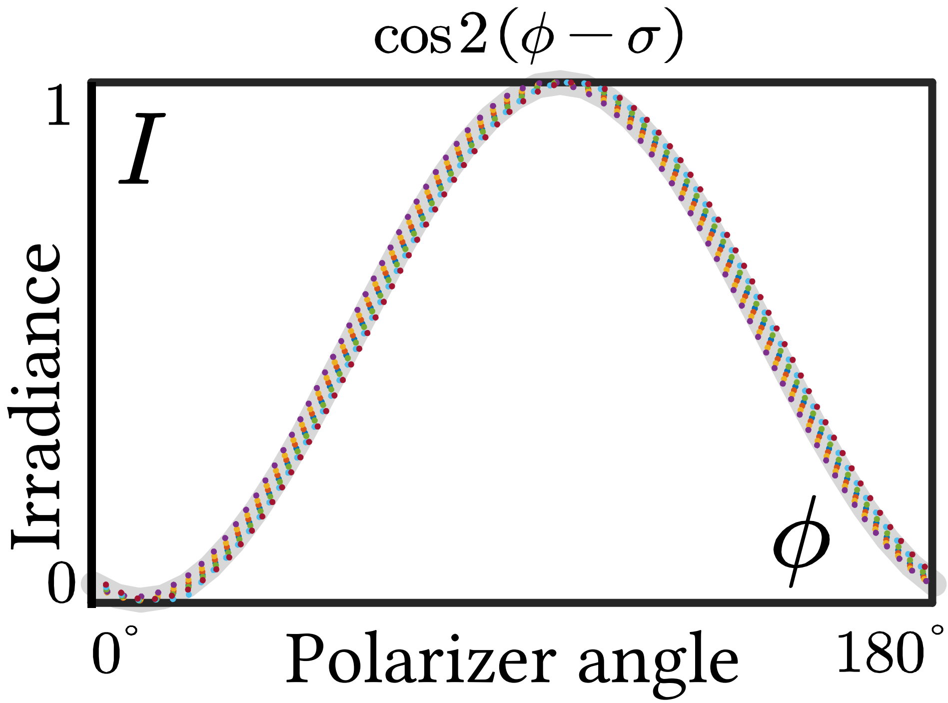

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LCD monitors

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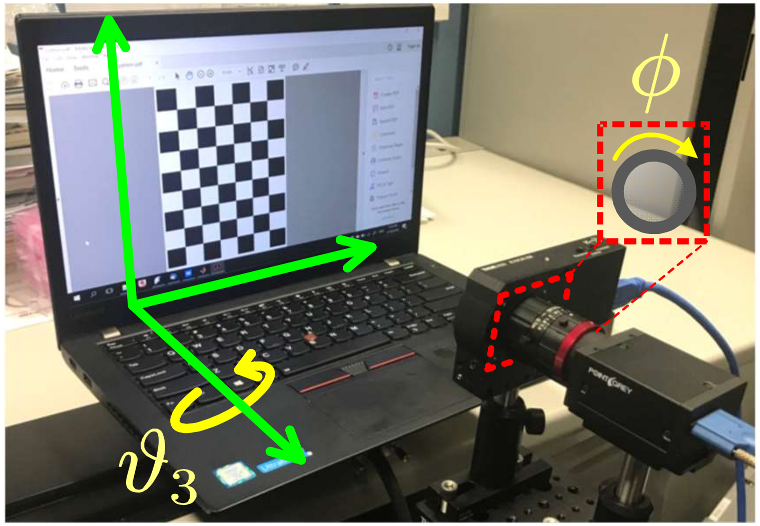
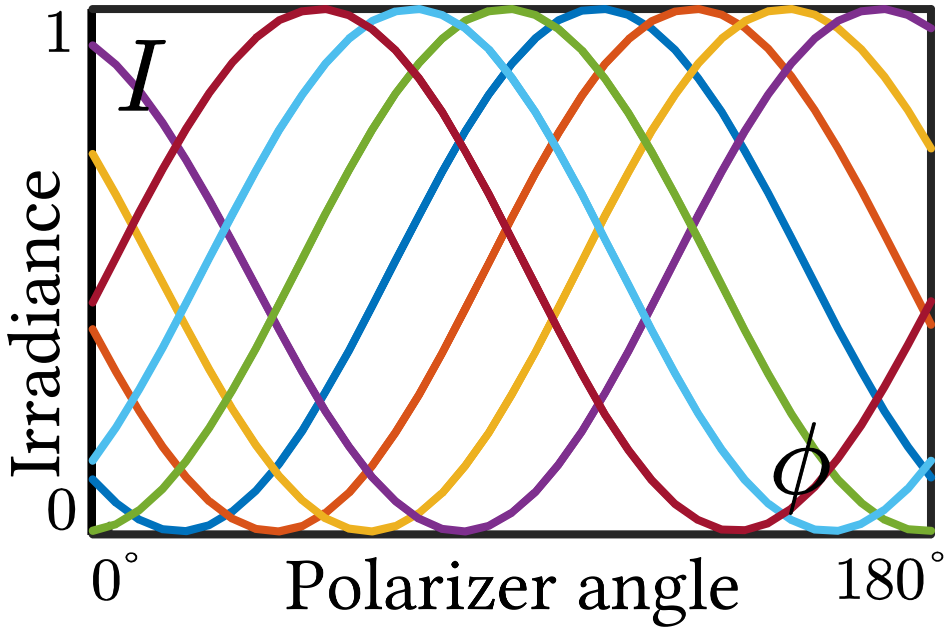


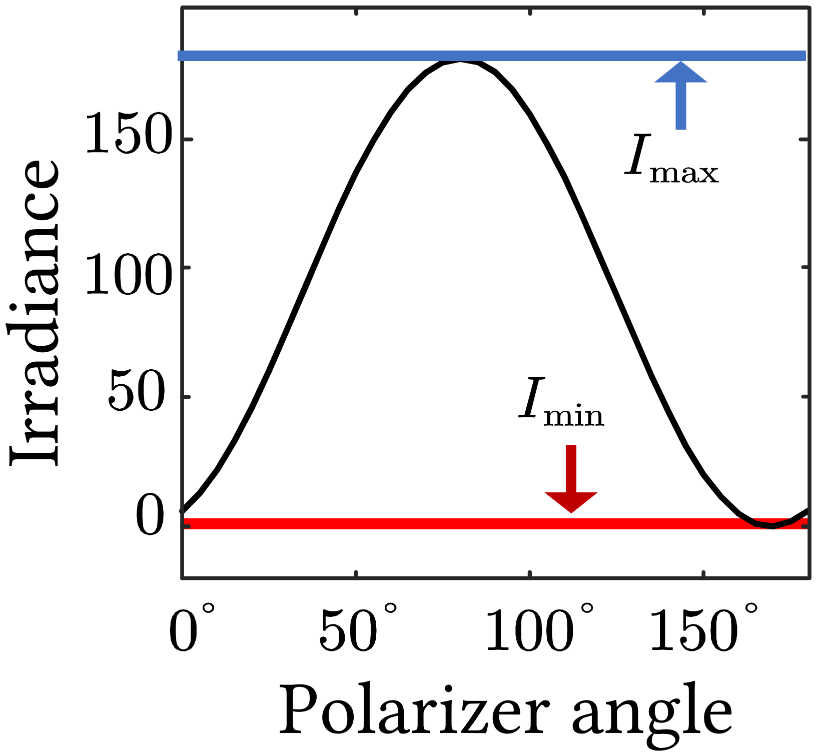
$\cos 2(\phi - \vartheta_3)$



Introduction – Motivation

LCD monitors

Characteristics B. Complete linear polarization



$$I_{max} \gg I_{min}$$

Introduction – Motivation

Pattern-based calibration

self-calibration

	Is easy to select points?	Can work ≤3 polar. channels?	Is robust to nonlinear CRF?	Is robust to initialization?	Radiometry?	Geometry?
ICCP'15	✗	✗	✗	✗	✗	✗
CVPR'18	✗	✗	✗	✗	✓	✗
Ours	✓	✓	✓	✓	✓	✓

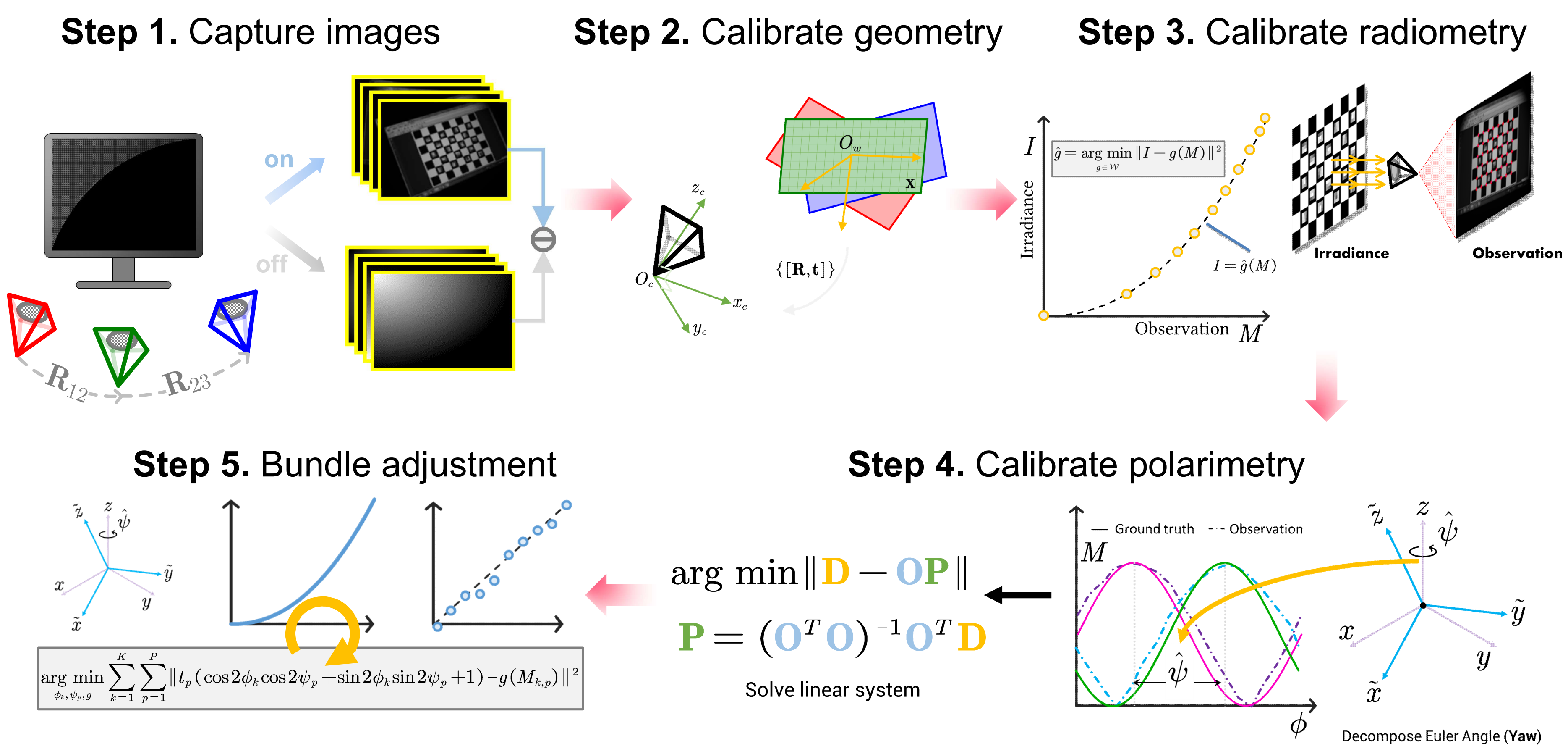
[Schechner et al. ICCP'15]

$$g(M_{k,p}) = I_{k,p} = t_p + a_p \cos[2(\boxed{\phi_k} - \psi_p)]$$

[Teo et al. CVPR'18]

Method

Overview

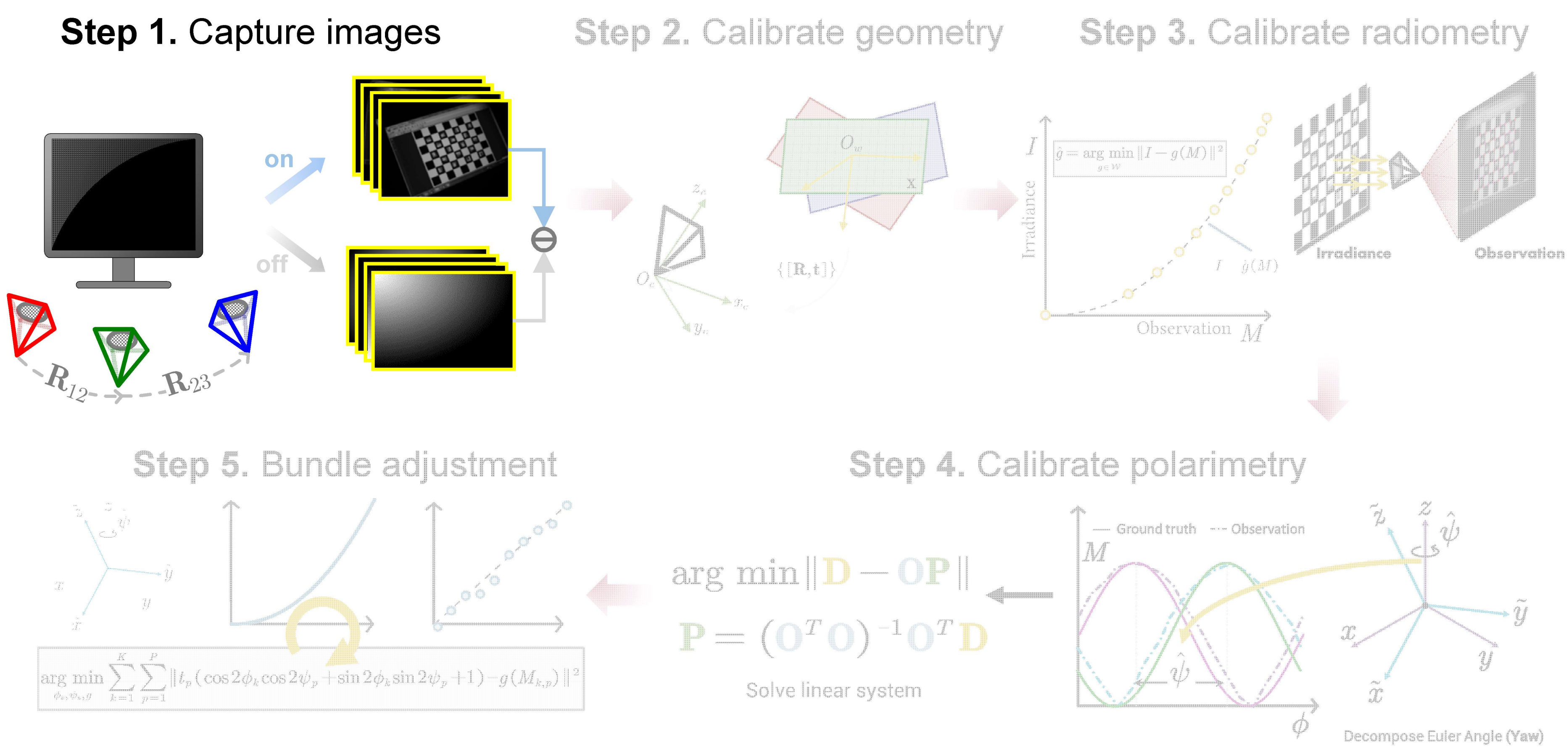


Method

$$\hat{g}(M_{k,p}) = t_p + a_p \cos 2(\boxed{\phi_k} - \hat{\psi}_p)$$

Method

Overview



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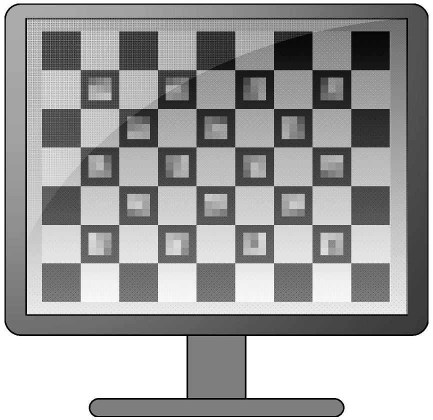

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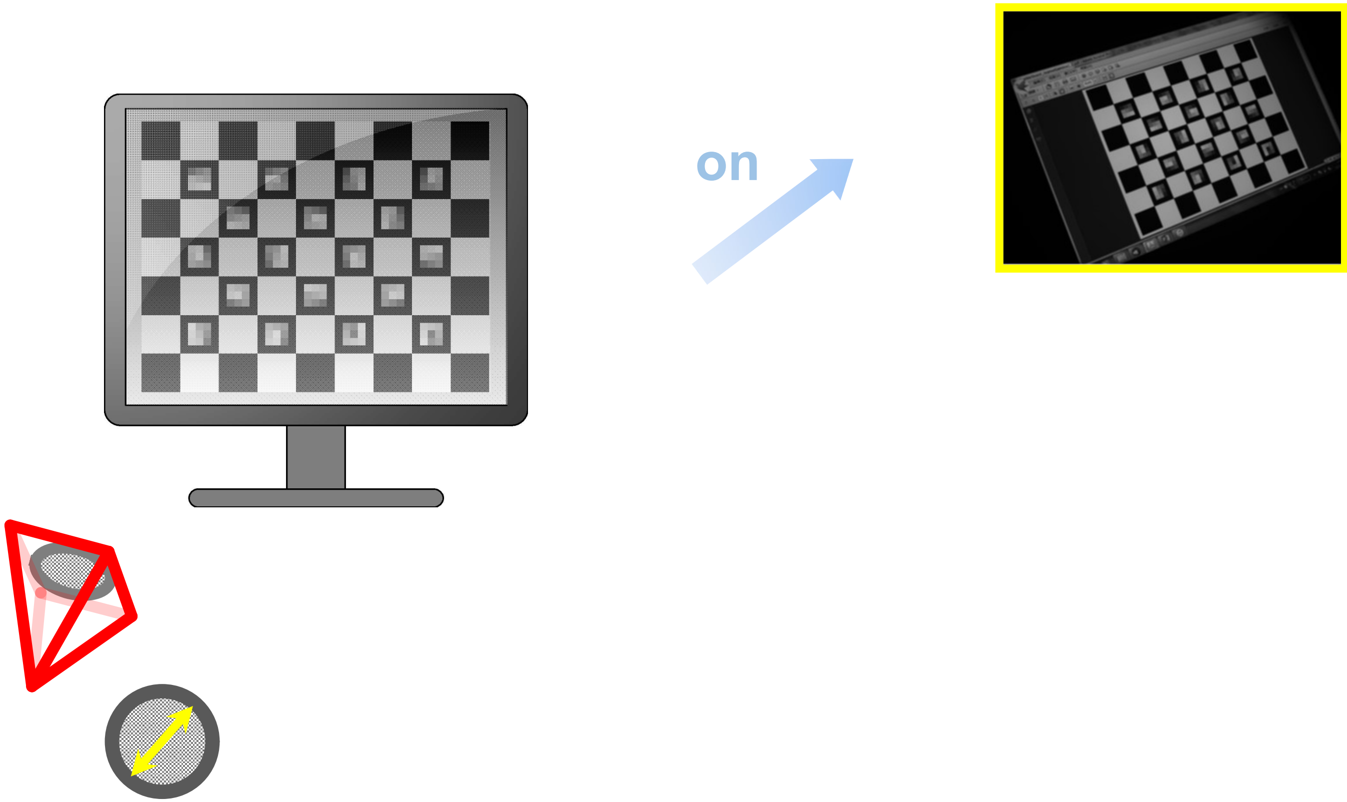

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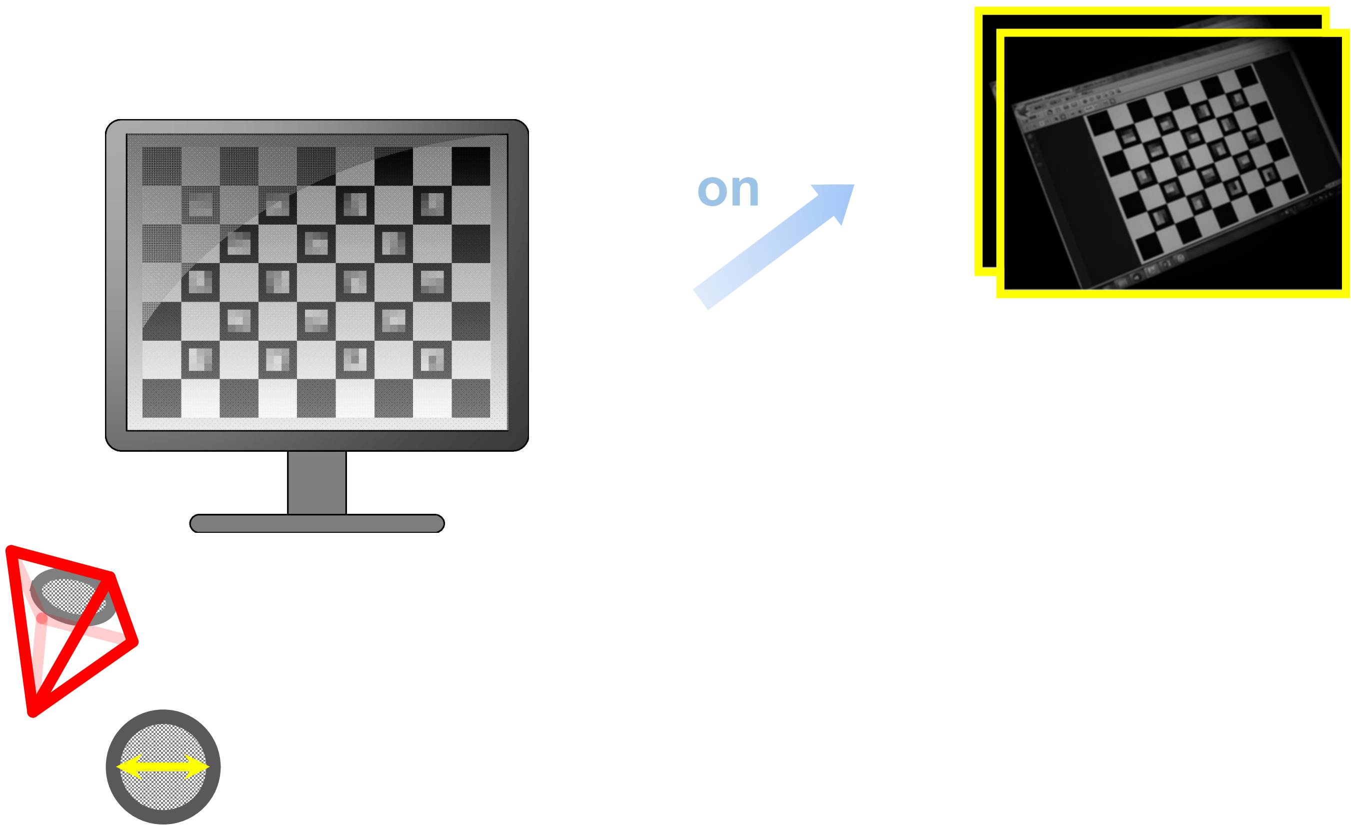

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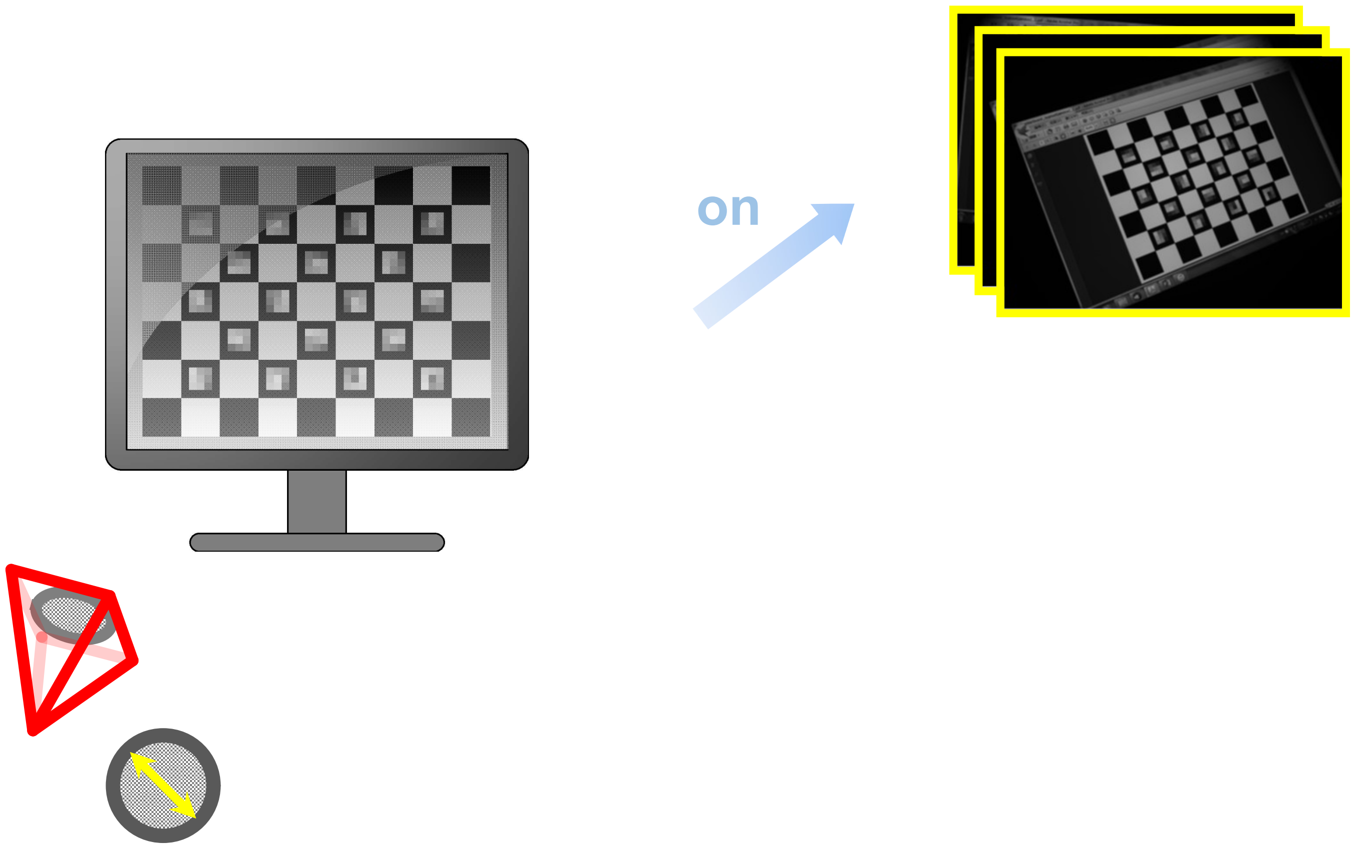

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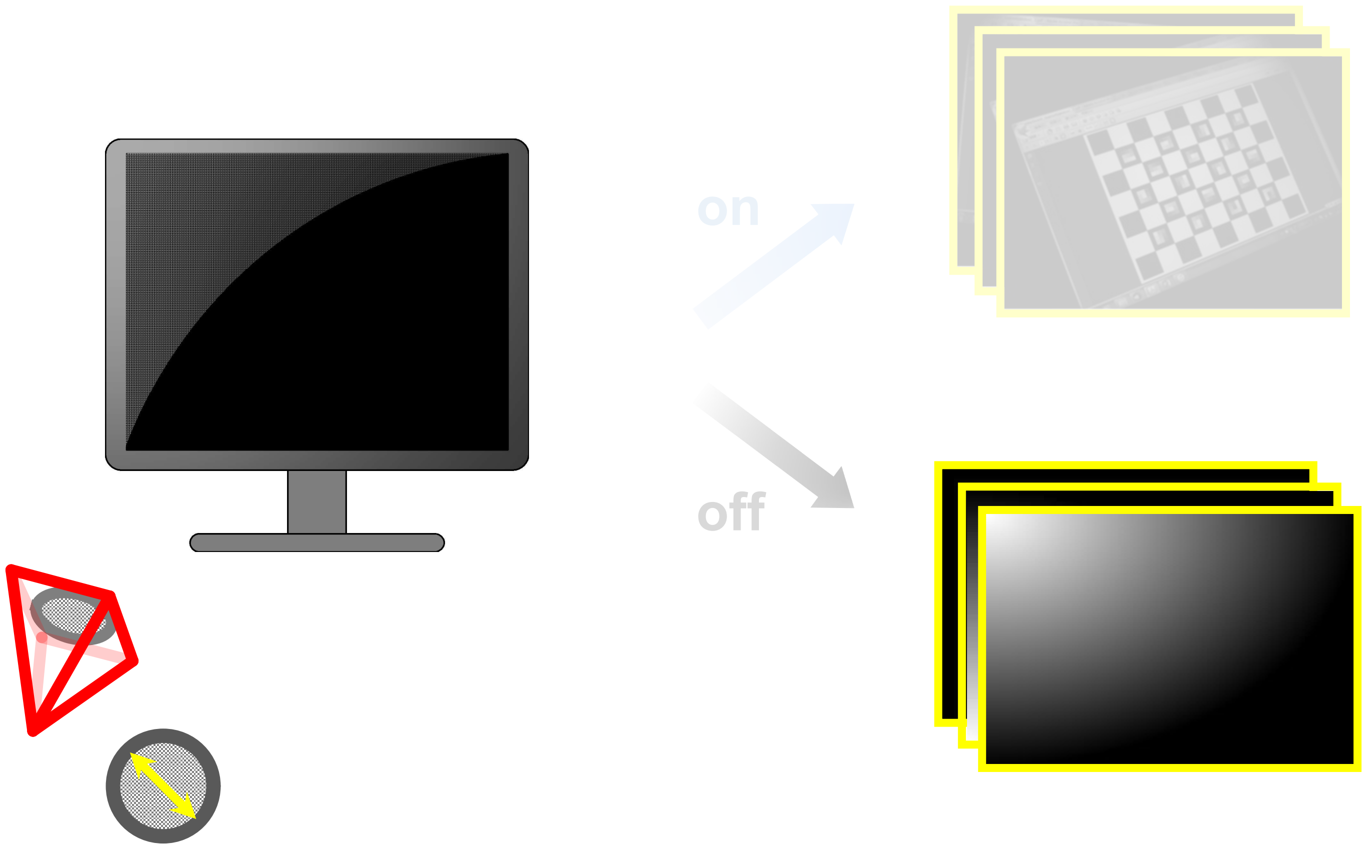

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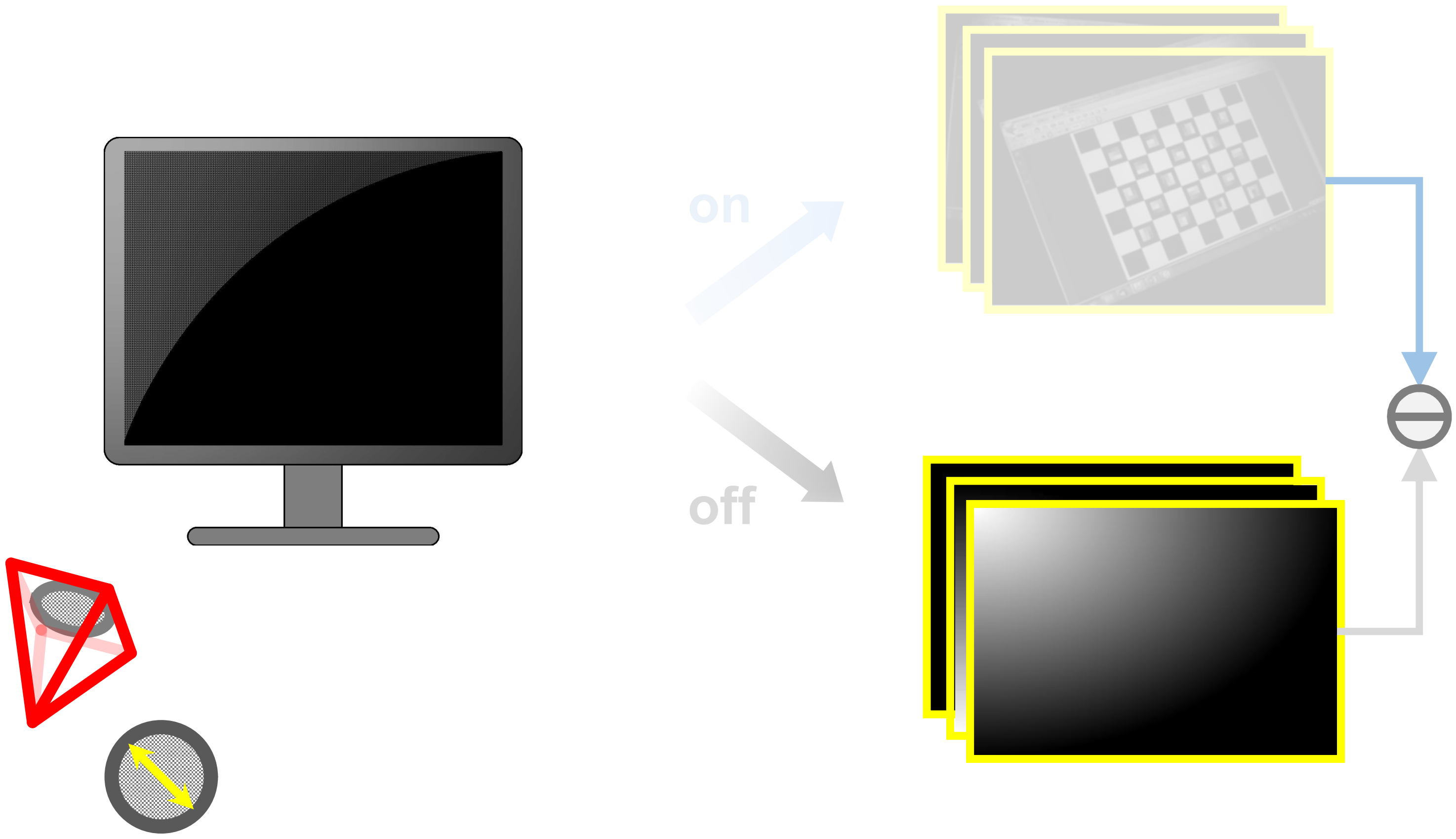

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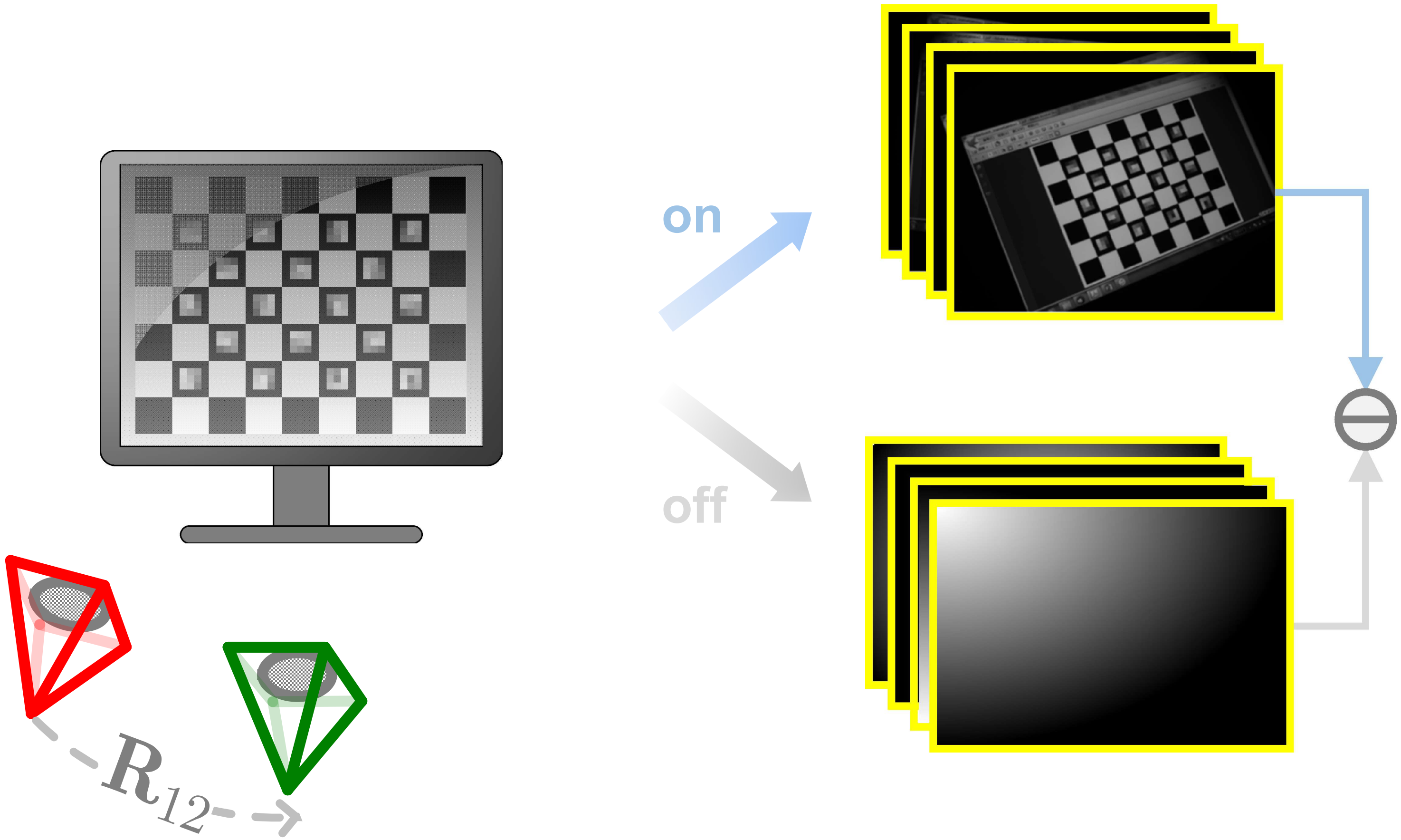

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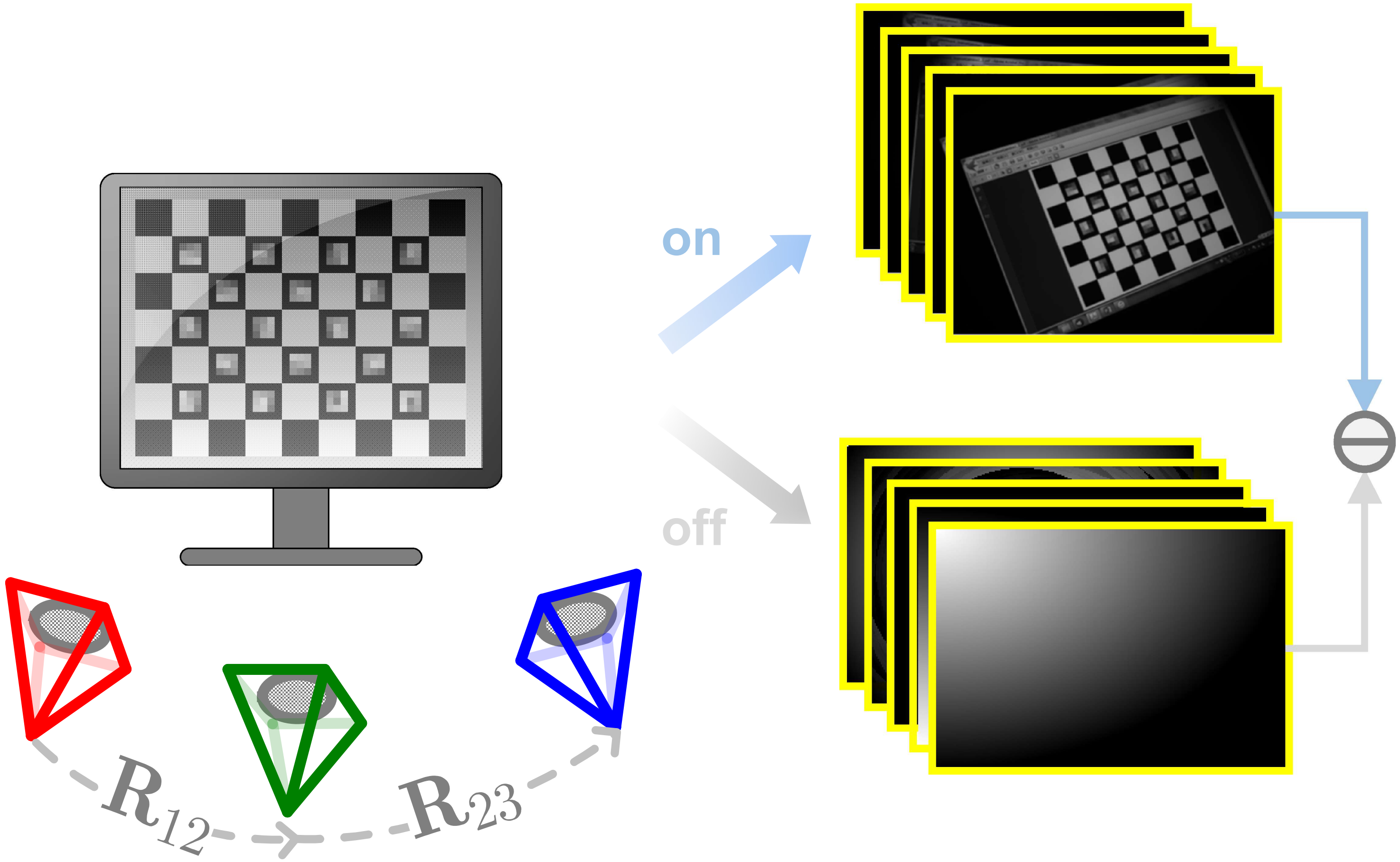


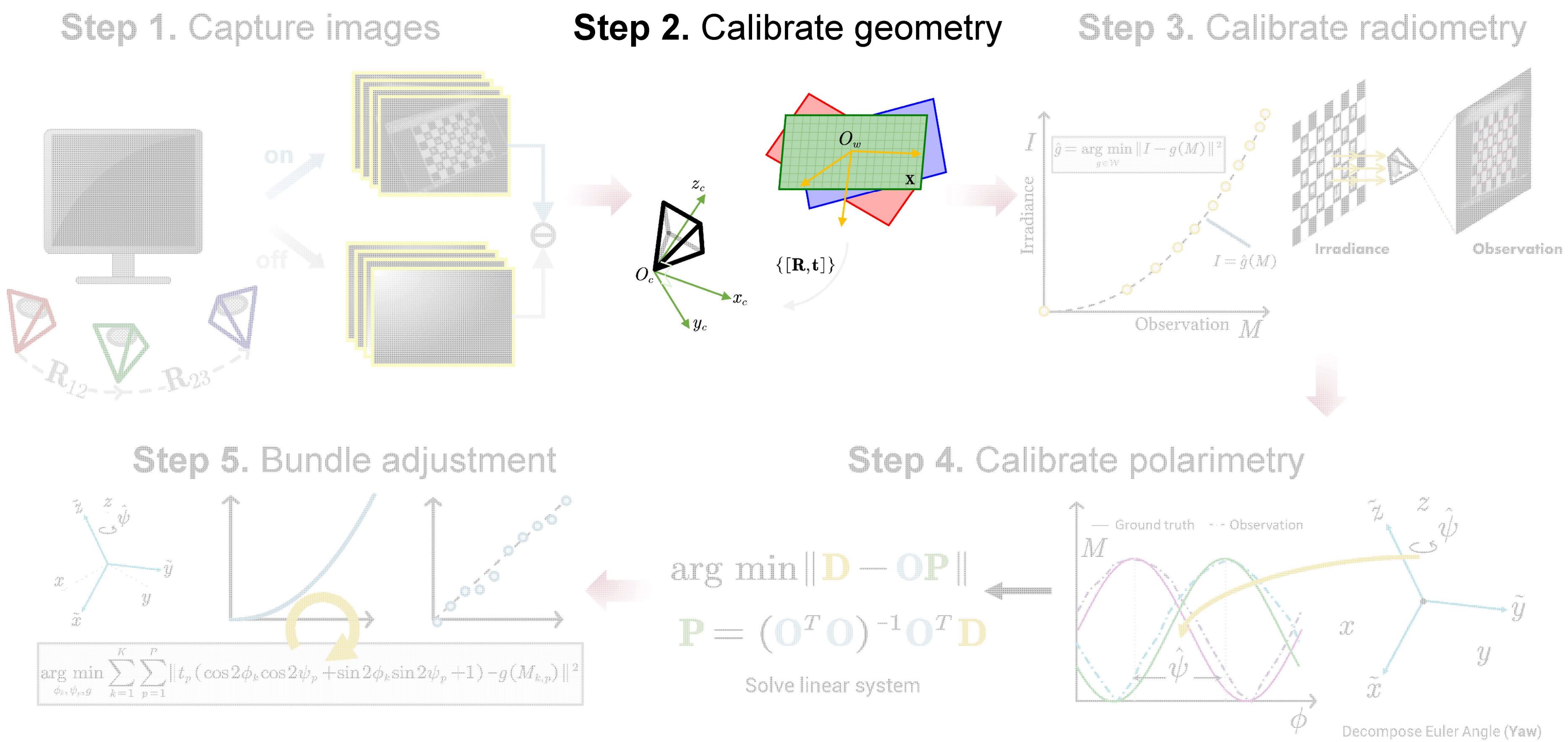
Method

$$\hat{g}(M_{k,p}) = t_p + a_p \cos 2(\boxed{\phi_k} - \hat{\psi}_p)$$

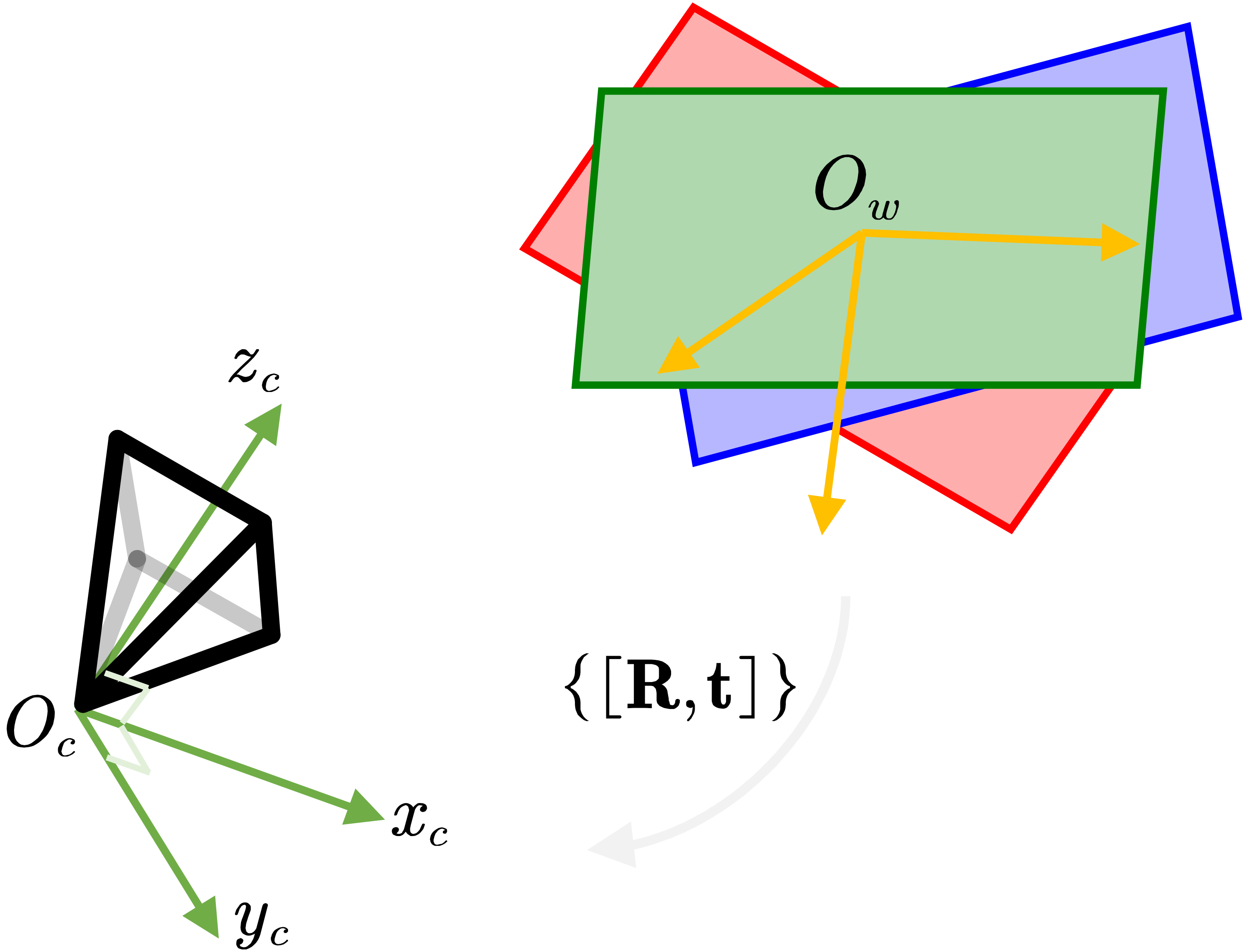
? ✓ ? ? ? ?

Method

Overview



Method – Known CRF



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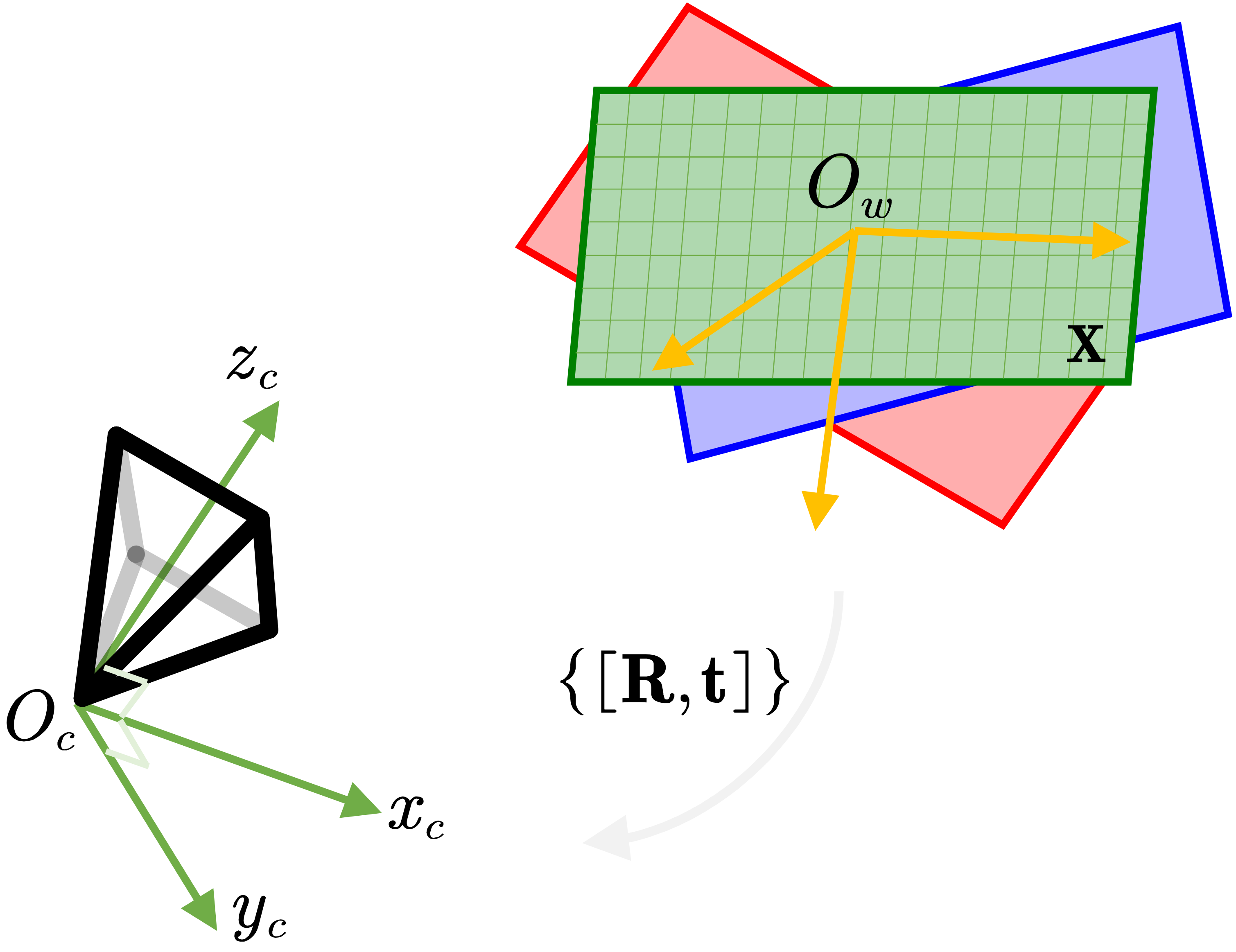

Method

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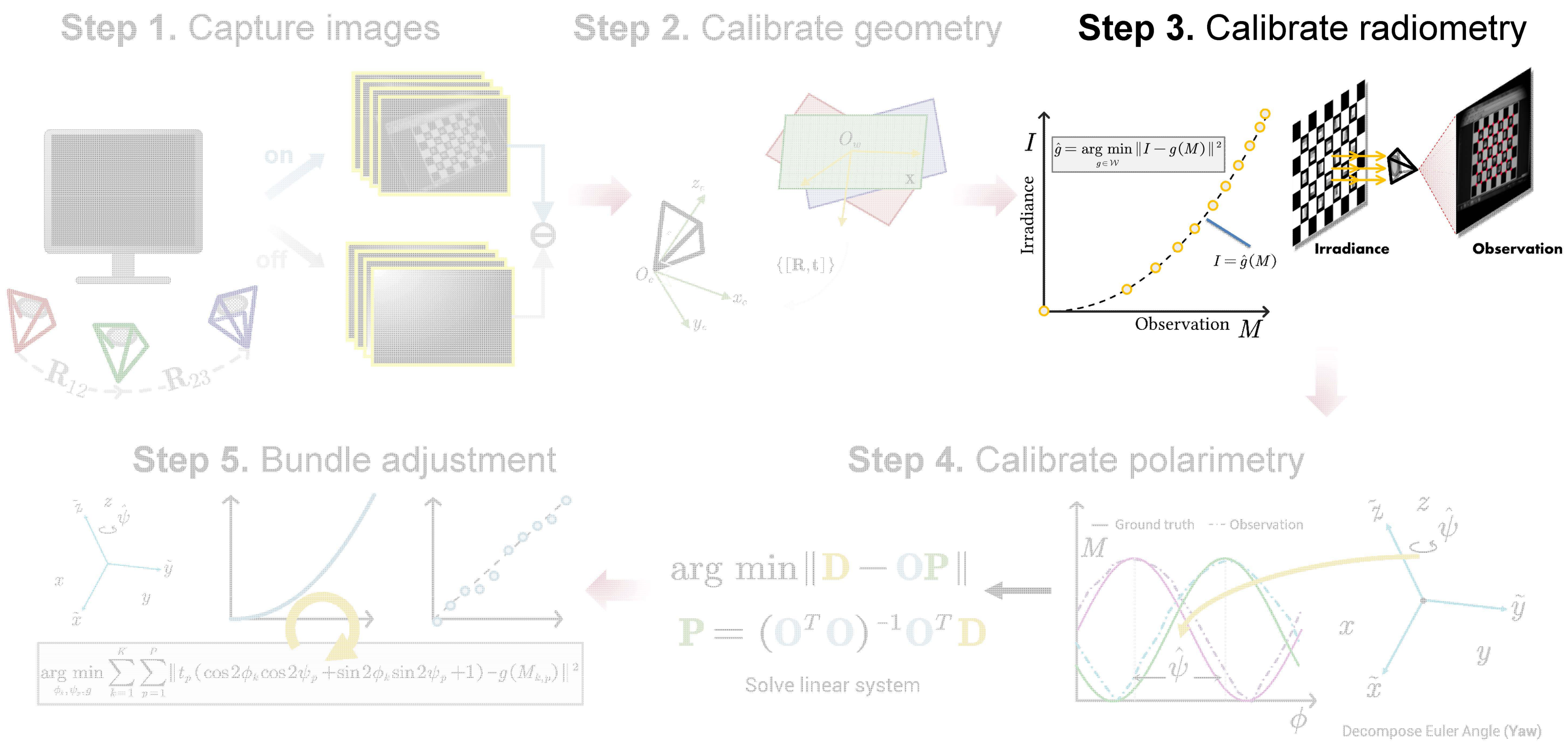

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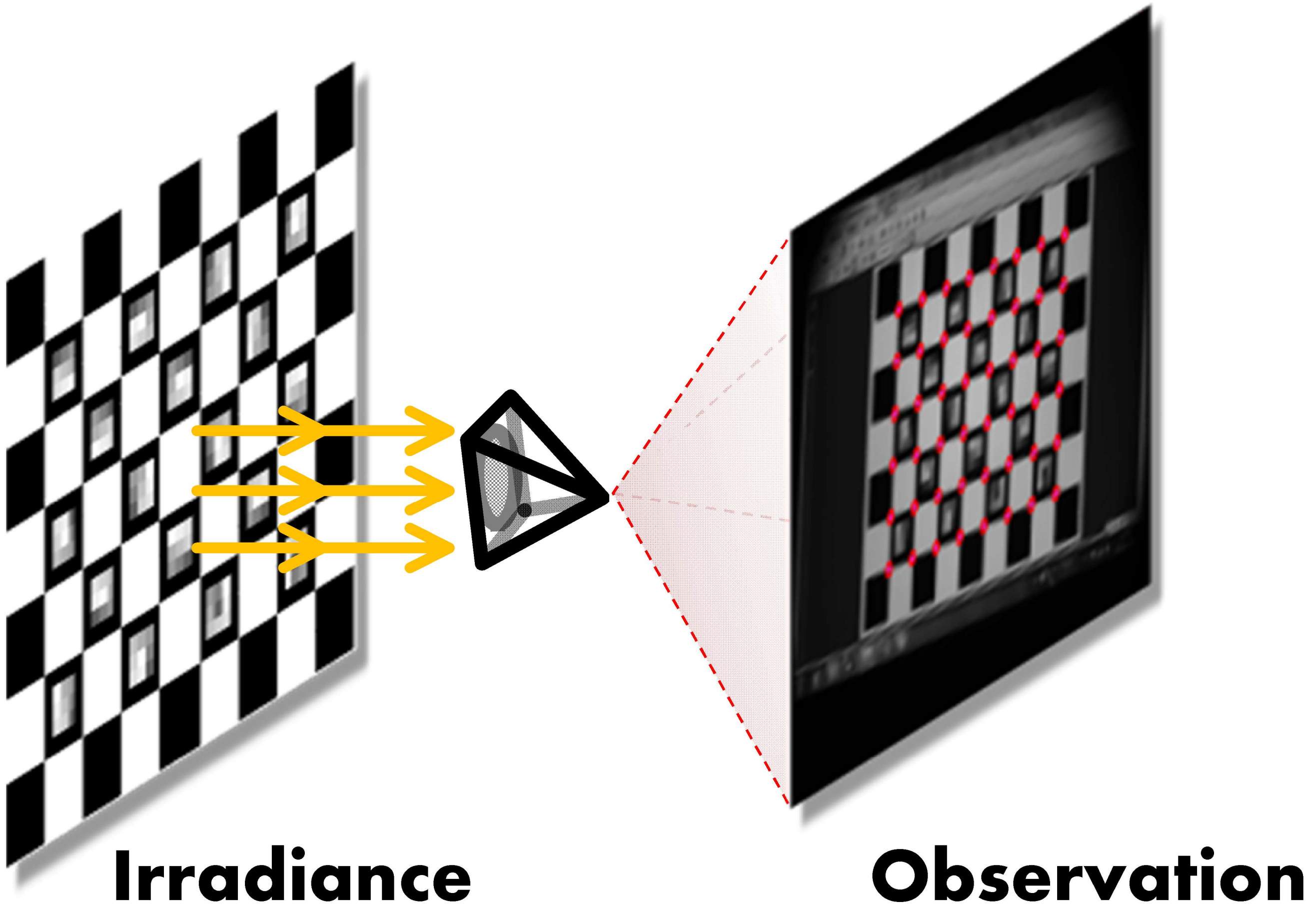
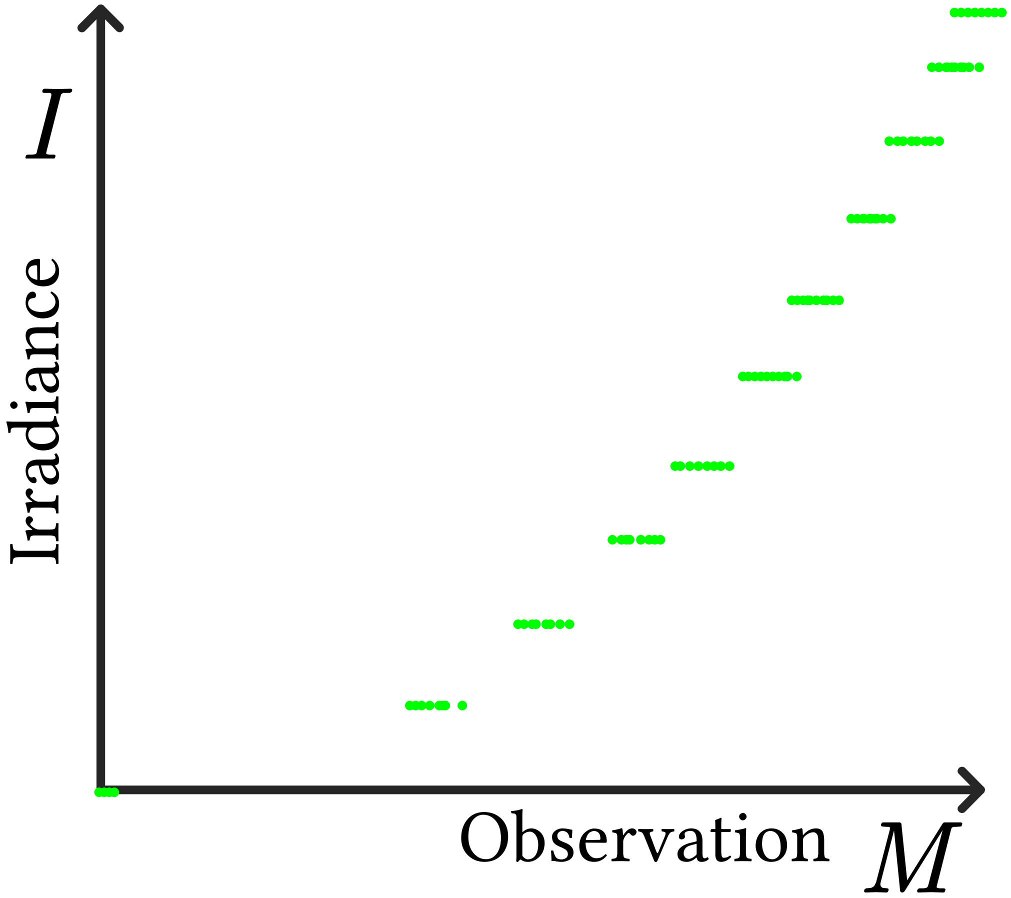
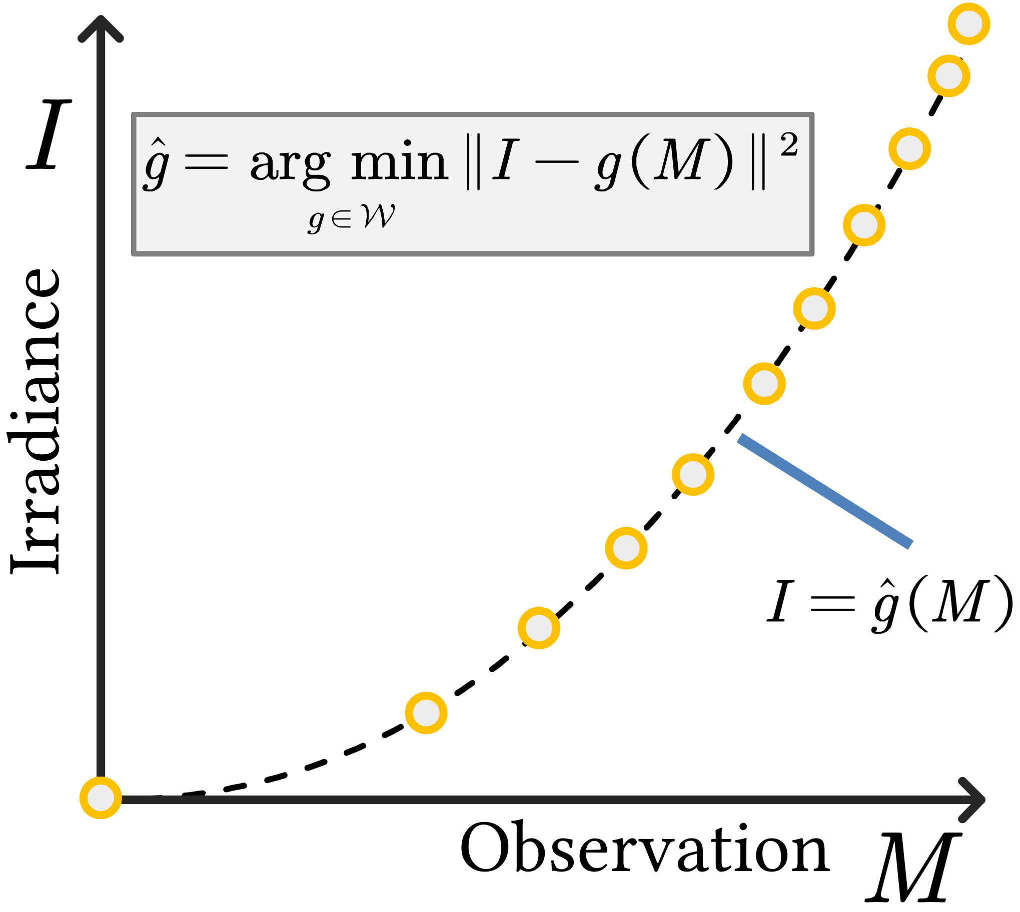


Method



Method



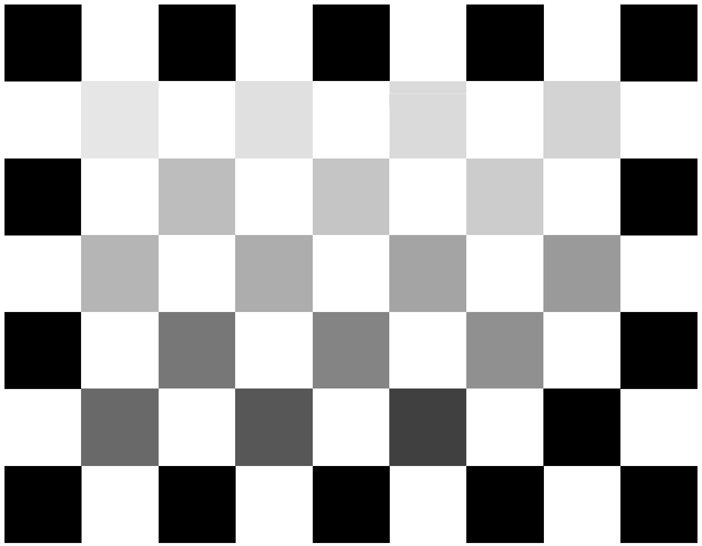
$\hat{g} = \underset{g \in \mathcal{W}}{\arg\min} \| I - g(M) \|^2$
I
Irradiance
Observation
M
$I = \hat{g}(M)$

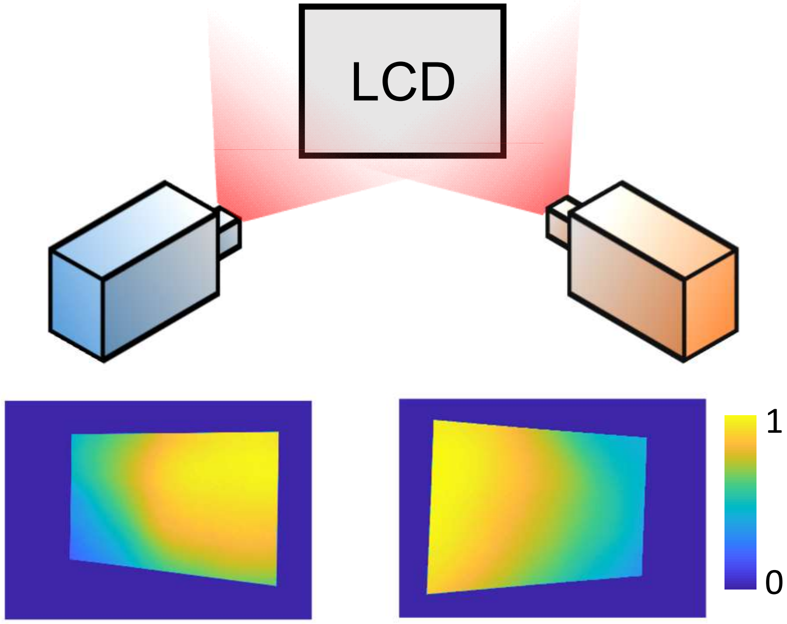
Method

$$\hat{g}(M_{k,p}) = t_p + a_p \cos 2(\boxed{\phi_k} - \hat{\psi}_p)$$

✓ ✓ ? ? ? ?

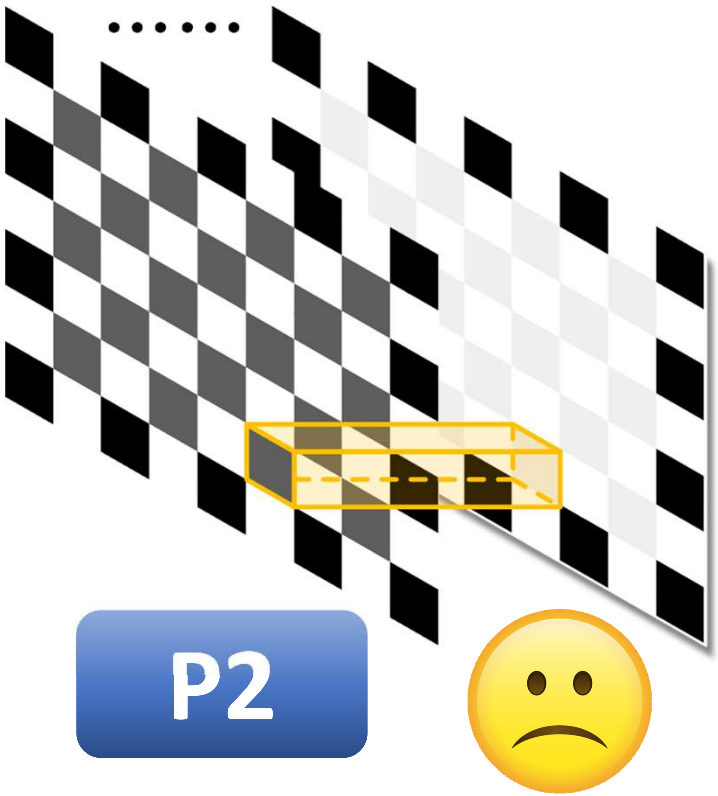
Method



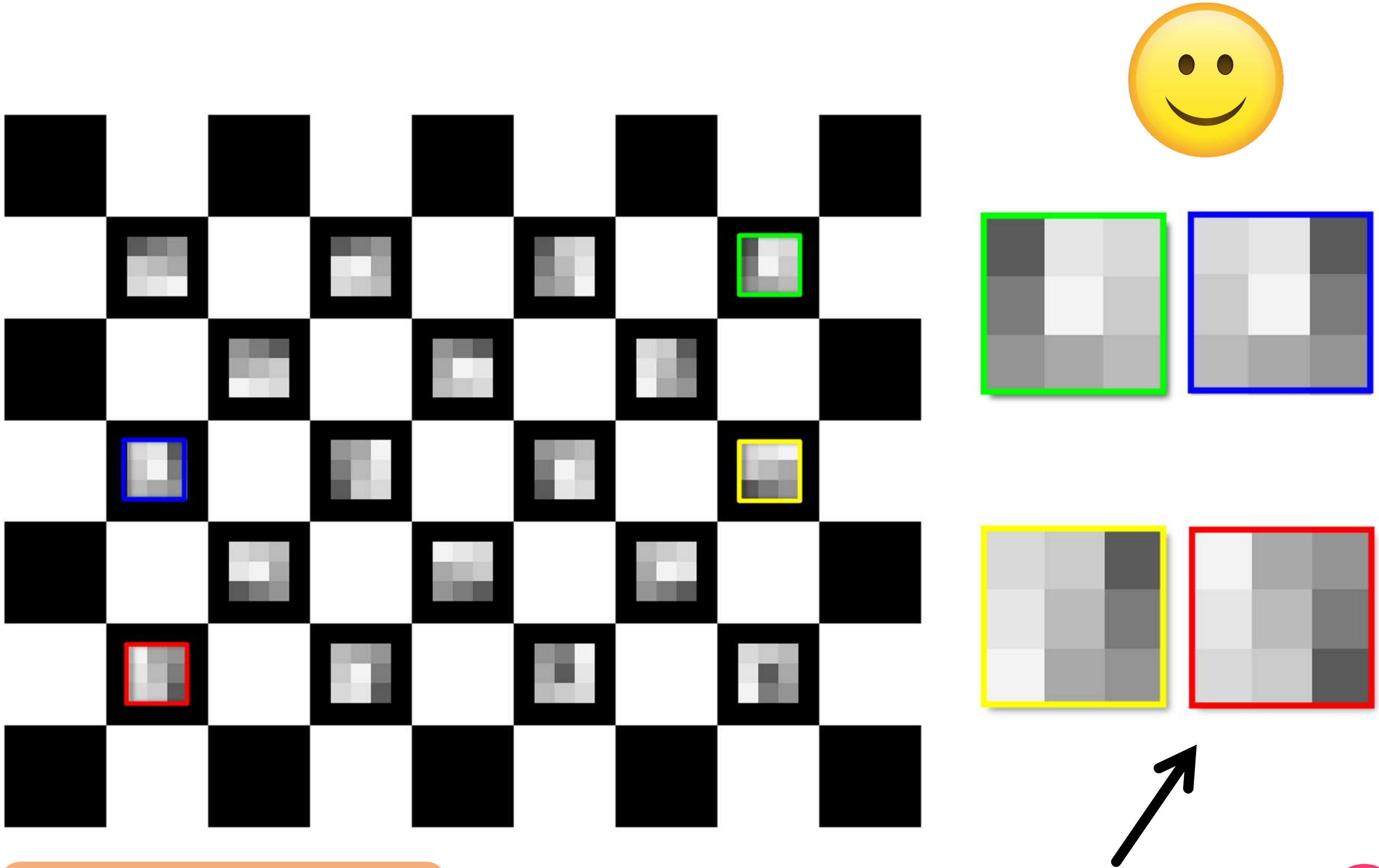


Spatial inconsistency

Method



Method

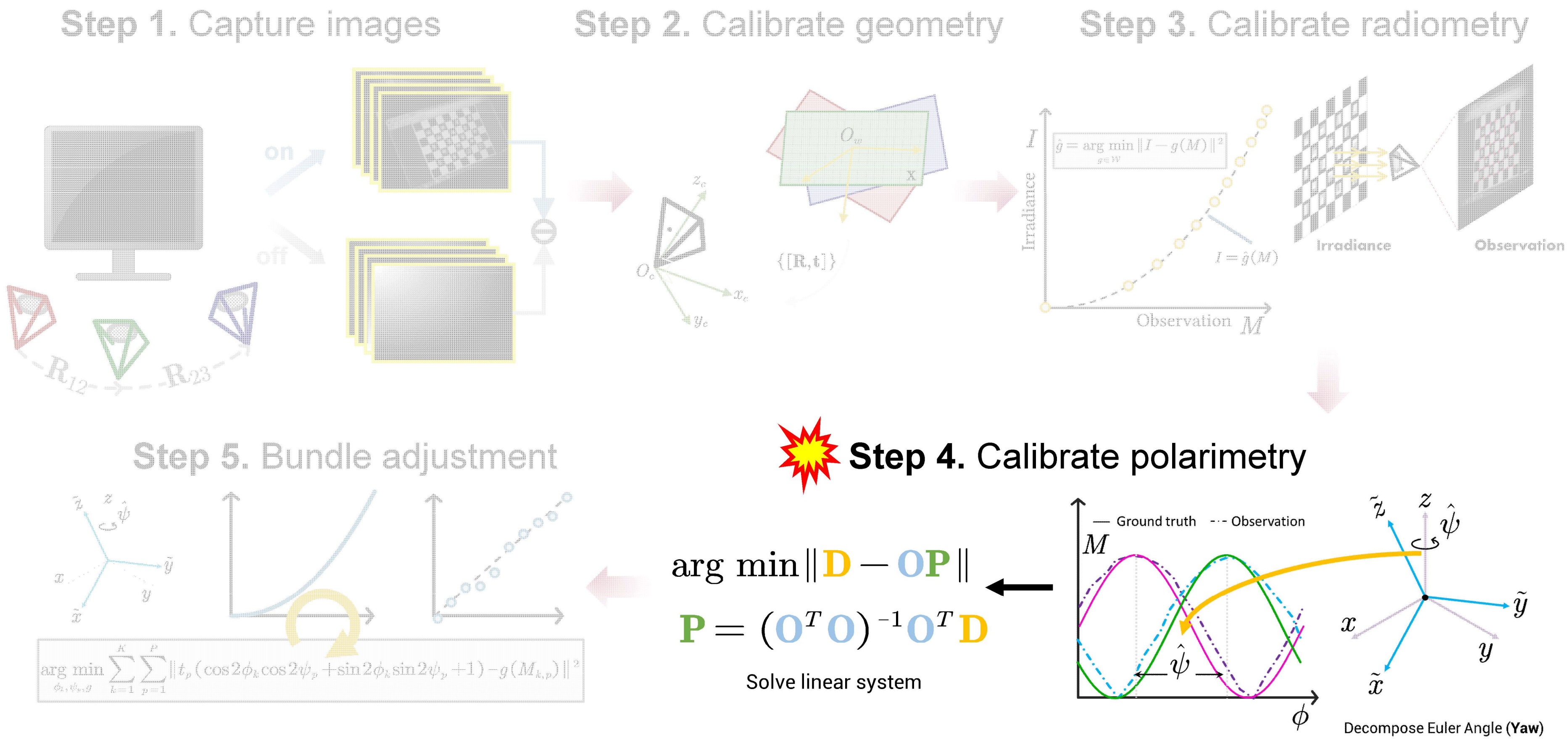


P3 (Ours)

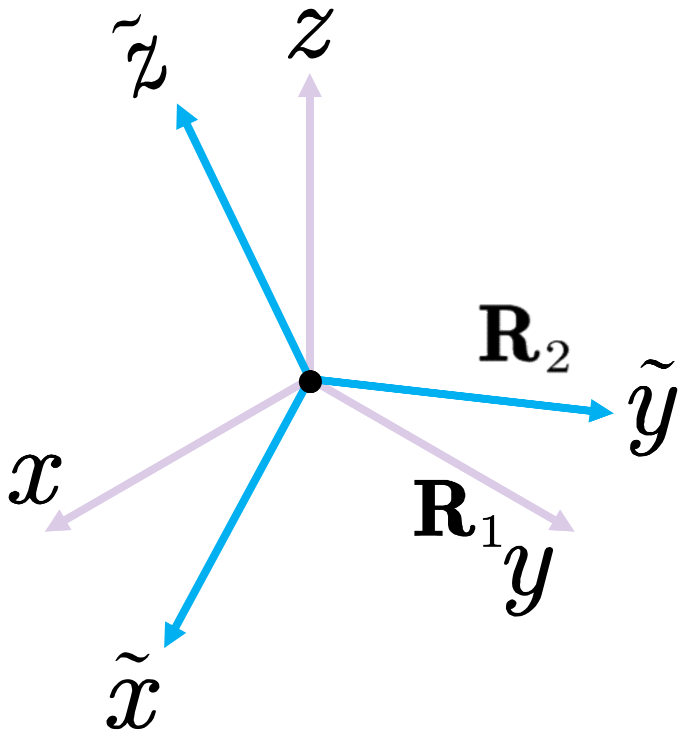
$$I_t = 255 \times [0.1, 0.2, ..., 0.9]^{1/\gamma}$$

Method

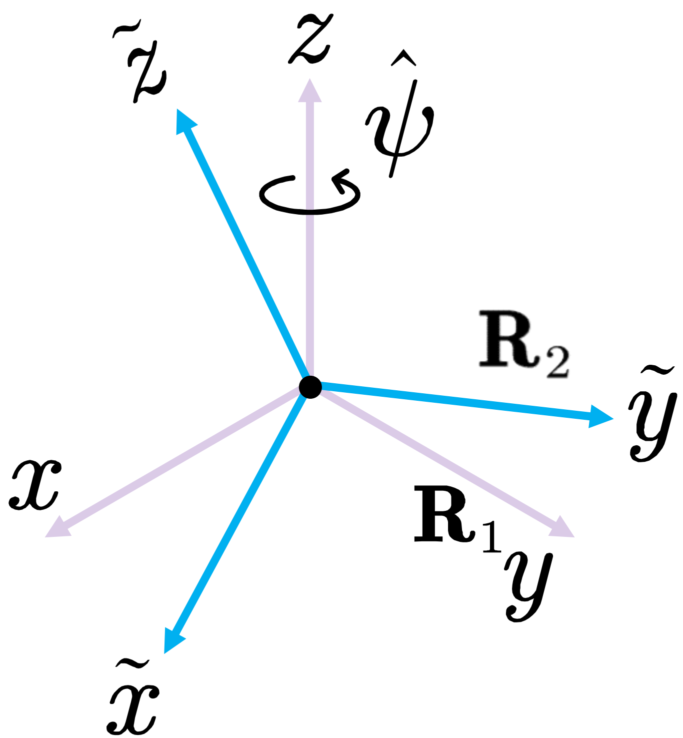
Overview



Method

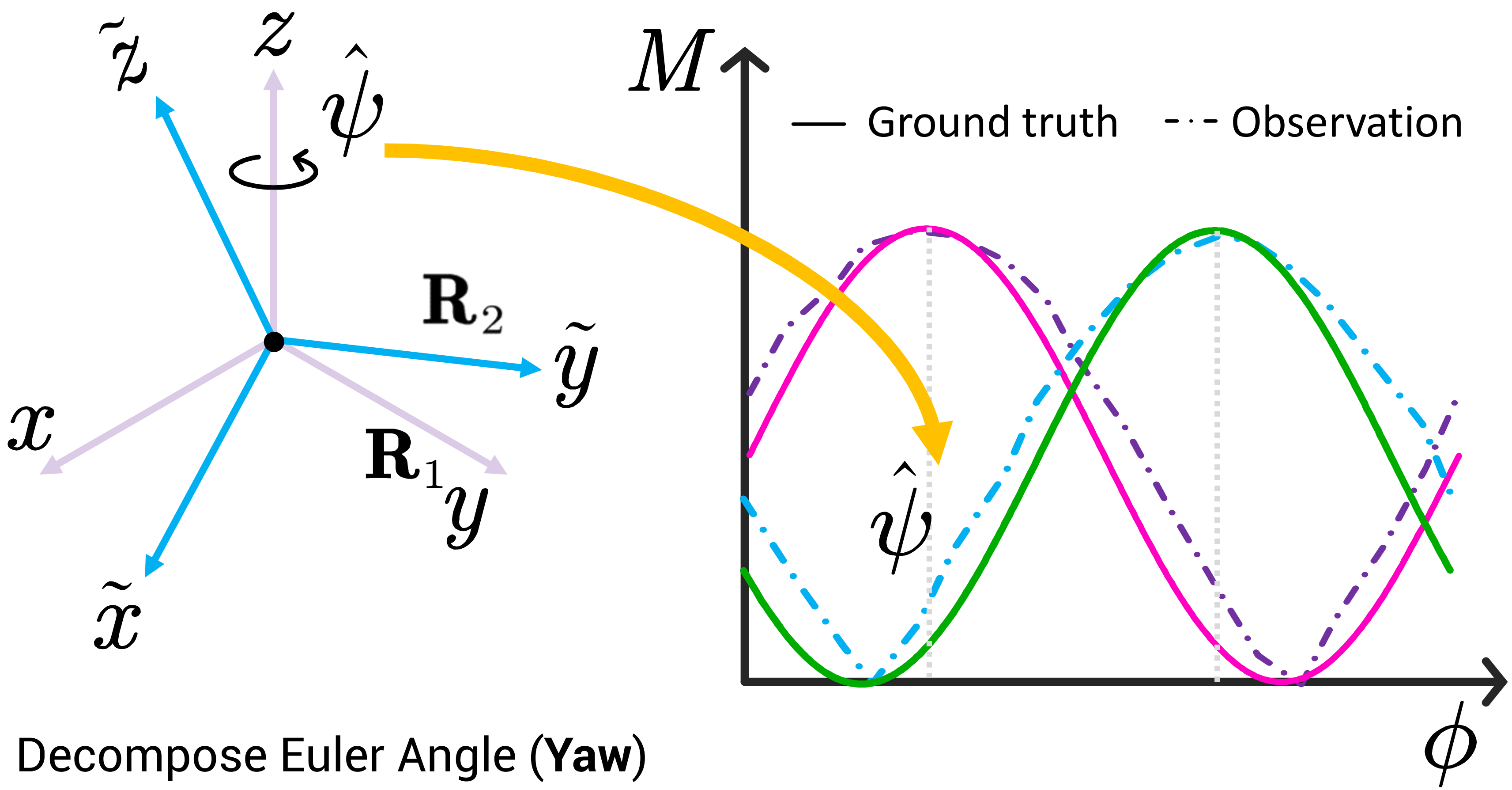


Method



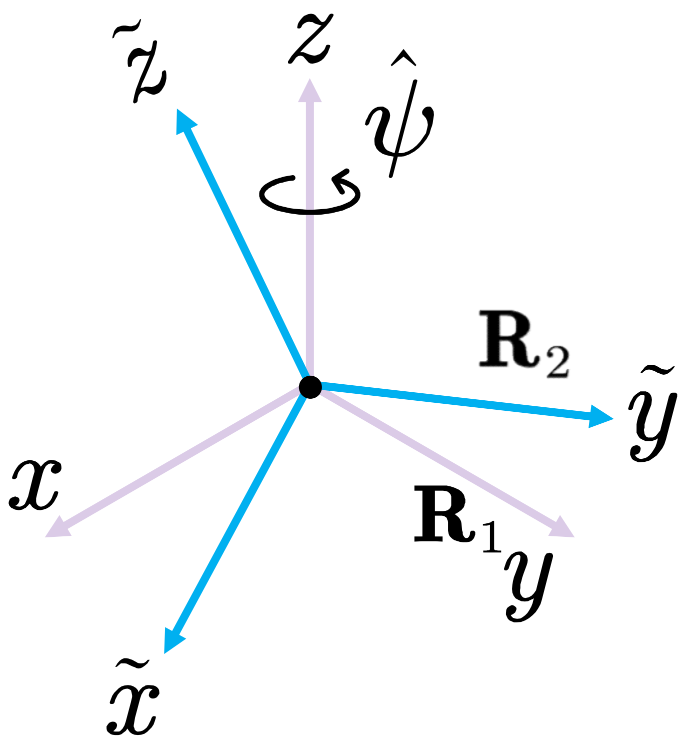
Decompose Euler Angle (**Yaw**)

Method



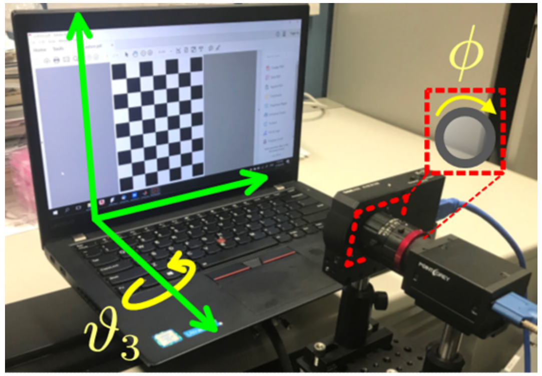
Decompose Euler Angle (**Yaw**)

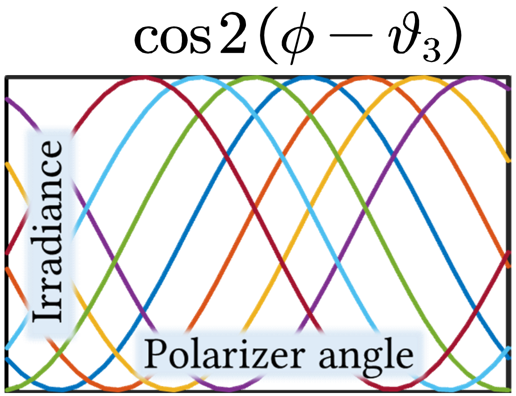
Method



Decompose Euler Angle (**Yaw**)

Recall: in-plane rotation





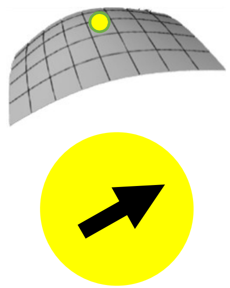
Method

$$\hat{g}(M_{k,p}) = t_p + a_p \cos 2(\boxed{\phi_k} - \hat{\psi}_p)$$

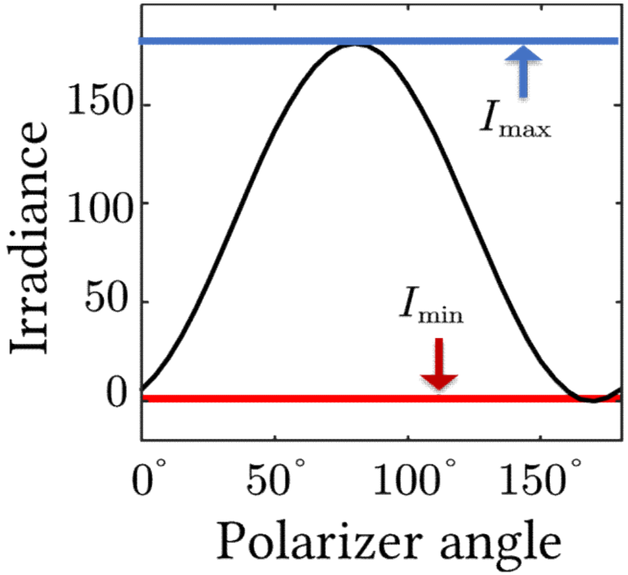
Method

$$\hat{g}(M_{k,p}) = t_p + a_p \cos 2\left(\phi_k - \hat{\psi}_p\right)$$

where $\boxed{\begin{aligned} t_p &= (I_{\max}(p) + I_{\min}(p))/2 \\ a_p &= (I_{\max}(p) - I_{\min}(p))/2 \end{aligned}}$



Recall $\boxed{I_{\max} \gg I_{\min}}$



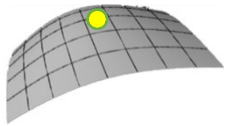
let $t_p = a_p = I_{\max}(p)/2$

$$\hat{g}(M_{k,p}) = t_p + \overset{t_p}{\cancel{a_p}} \cos 2\left(\phi_k - \hat{\psi}_p\right)$$

Method

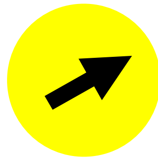
$$\hat{g}(M_{k,p}) = t_p + a_p \cos 2(\boxed{\phi_k} - \hat{\psi}_p)$$

Method



$$\hat{g}(M_{k,p}) = t_p + t_p \cos 2\left(\phi_k - \hat{\psi}_p\right)$$

$$\hat{g}(M_{k,p}) = t_p\,(1 + \overset{\alpha_p}{\cos 2\psi_k} \cos 2\boxed{\phi_k} + \overset{\beta_p}{\sin 2\psi_k} \sin 2\boxed{\phi_k})$$

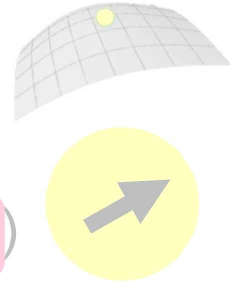


?

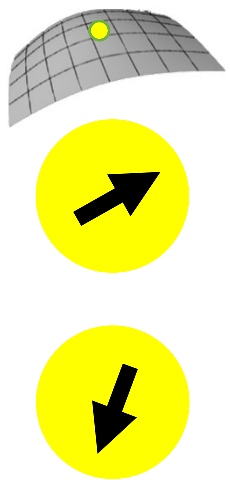
Method

$$\hat{g}(M_{k,p}) = t_p + t_p \cos 2\left(\phi_k - \hat{\psi}_p\right)$$

$$\hat{g}(M_{k,p}) = t_p\,(1 + \overset{\alpha_p}{\cos 2\psi_k} \cos 2\boxed{\phi_k} + \overset{\beta_p}{\sin 2\psi_k} \sin 2\boxed{\phi_k})$$



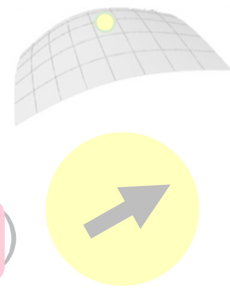
$$\hat{g}(M_{k,p}) = t_p\,(1 + \alpha_p \cos 2\phi_k + \beta_p \sin 2\phi_k)$$
$$\hat{g}(M_{1,p}) = t_p\,(1 + \alpha_p \cos 2\phi_1 + \beta_p \sin 2\phi_1)$$



Method

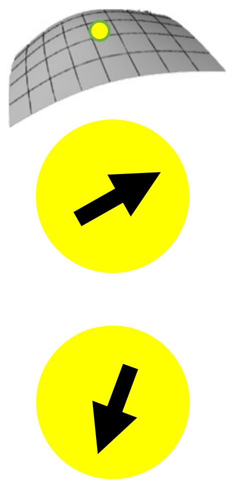
$$\hat{g}(M_{k,p}) = t_p + t_p \cos 2\left(\phi_k - \hat{\psi}_p\right)$$

$$\hat{g}(M_{k,p}) = t_p\,(1 + \overset{\alpha_p}{\cos 2\psi_k} \cos 2\boxed{\phi_k} + \overset{\beta_p}{\sin 2\psi_k} \sin 2\boxed{\phi_k})$$



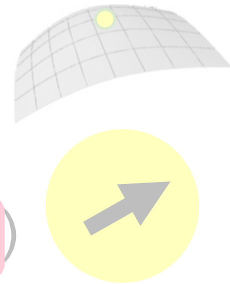
$$\frac{\hat{g}(M_{k,p})}{\hat{g}(M_{1,p})} = \frac{1 + \alpha_p \cos 2\phi_k + \beta_p \sin 2\phi_k}{1 + \alpha_p \cos 2\phi_1 + \beta_p \sin 2\phi_1}$$

where $\hat{g}(M_{1,p}) \neq 0$ $\quad \phi_1 \neq \hat{\psi}_p \pm \pi/2$



Method

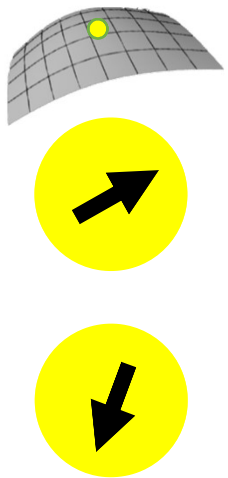
$$\hat{g}(M_{k,p}) = t_p + t_p \cos 2\left(\phi_k - \hat{\psi}_p\right)$$



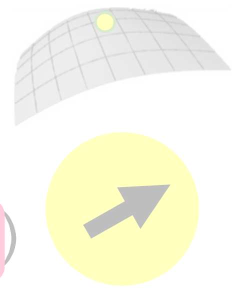
$$\hat{g}(M_{k,p}) = t_p\,(1 + \overbrace{\cos 2\psi_k}^{\alpha_p} \cos 2\boxed{\phi_k} + \overbrace{\sin 2\psi_k}^{\beta_p} \sin 2\boxed{\phi_k})$$

?

$$\frac{\hat{g}(M_{k,p})}{\hat{g}(M_{1,p})} = \frac{1 + \alpha_p \cos 2\phi_k + \beta_p \sin 2\phi_k}{1 + \alpha_p \cos 2\phi_1 + \beta_p \sin 2\phi_1}$$



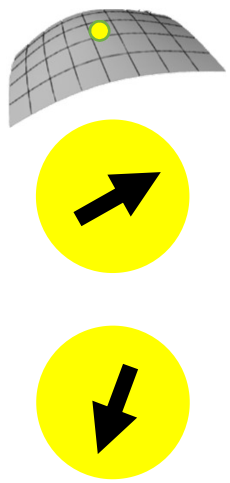
Method



$$\hat{g}(M_{k,p}) = t_p + t_p \cos 2(\phi_k - \hat{\psi}_p)$$

$$\hat{g}(M_{k,p}) = t_p (1 + \overbrace{\cos 2\psi_k}^{\alpha_p} \cos 2\boxed{\phi_k} + \overbrace{\sin 2\psi_k}^{\beta_p} \sin 2\boxed{\phi_k})$$

?



$$\frac{\hat{g}(M_{k,p})}{\hat{g}(M_{1,p})} = \frac{1 + \alpha_p \cos 2\phi_k + \beta_p \sin 2\phi_k}{1 + \alpha_p \cos 2\phi_1 + \beta_p \sin 2\phi_1}$$

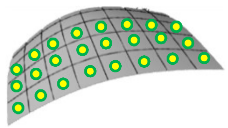
$$I_{k,p} - I_{1,p} = I_{1,p}\alpha_p \cos 2\phi_k + I_{1,p}\beta_p \sin 2\phi_k$$
$$-I_{k,p}\alpha_p \cos 2\phi_1 + I_{k,p}\beta_p \sin 2\phi_1$$

where $I_{k,p} = \hat{g}(M_{k,p})$

Method

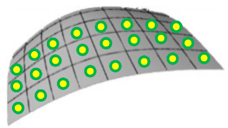
$$\hat{g}(M_{k,p}) = t_p + a_p \cos 2(\boxed{\phi_k} - \hat{\psi}_p)$$

Method



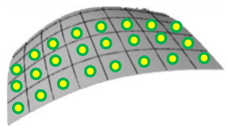
$$
\begin{bmatrix} \hat{I}_{1,1} - \hat{I}_{2,1} \\ \vdots \\ \hat{I}_{1,P} - \hat{I}_{2,P} \\ \vdots \\ \hat{I}_{1,1} - \hat{I}_{K,1} \\ \vdots \\ \hat{I}_{1,P} - \hat{I}_{K,P} \end{bmatrix}
=
\begin{bmatrix}
\begin{matrix} \alpha_1 \hat{I}_{2,1} & \beta_1 \hat{I}_{2,1} \\ \alpha_2 \hat{I}_{2,2} & \beta_2 \hat{I}_{2,2} \\ \vdots & \vdots \\ \alpha_P \hat{I}_{2,P} & \beta_P \hat{I}_{2,P} \end{matrix} &
\begin{matrix} -\alpha_1 \hat{I}_{1,1} & -\beta_1 \hat{I}_{1,1} \\ -\alpha_2 \hat{I}_{1,2} & -\beta_2 \hat{I}_{1,2} \\ \vdots & \vdots \\ -\alpha_P \hat{I}_{1,P} & -\beta_P \hat{I}_{1,P} \end{matrix} &
\mathbf{0} & \cdots & \mathbf{0} \\
\begin{matrix} \alpha_1 \hat{I}_{3,1} & \beta_1 \hat{I}_{3,1} \\ \alpha_2 \hat{I}_{3,2} & \beta_2 \hat{I}_{3,2} \\ \vdots & \vdots \\ \alpha_P \hat{I}_{3,P} & \beta_P \hat{I}_{3,P} \end{matrix} &
\mathbf{0} &
\begin{matrix} -\alpha_1 \hat{I}_{1,1} & -\beta_1 \hat{I}_{1,1} \\ -\alpha_2 \hat{I}_{1,2} & -\beta_2 \hat{I}_{1,2} \\ \vdots & \vdots \\ -\alpha_P \hat{I}_{1,P} & -\beta_P \hat{I}_{1,P} \end{matrix} &
\cdots & \mathbf{0} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
\begin{matrix} \alpha_1 \hat{I}_{K,1} & \beta_1 \hat{I}_{K,1} \\ \alpha_2 \hat{I}_{K,2} & \beta_2 \hat{I}_{K,2} \\ \vdots & \vdots \\ \alpha_P \hat{I}_{K,P} & \beta_P \hat{I}_{K,P} \end{matrix} &
\mathbf{0} & \mathbf{0} & \cdots &
\begin{matrix} -\alpha_1 \hat{I}_{1,1} & -\beta_1 \hat{I}_{1,1} \\ -\alpha_2 \hat{I}_{1,2} & -\beta_2 \hat{I}_{1,2} \\ \vdots & \vdots \\ -\alpha_P \hat{I}_{1,P} & -\beta_P \hat{I}_{1,P} \end{matrix}
\end{bmatrix}
\begin{bmatrix} \cos 2\phi_1 \\ \sin 2\phi_1 \\ \vdots \\ \cos 2\phi_K \\ \sin 2\phi_K \end{bmatrix}
$$

Method



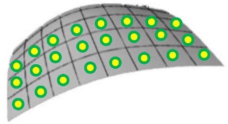
$$
\begin{bmatrix} \hat{I}_{1,1}-\hat{I}_{2,1} \\ \vdots \\ \hat{I}_{1,P}-\hat{I}_{2,P} \\ \vdots \\ \hat{I}_{1,1}-\hat{I}_{K,1} \\ \vdots \\ \hat{I}_{1,P}-\hat{I}_{K,P} \end{bmatrix}
=
\begin{bmatrix}
\begin{matrix} \alpha_1\hat{I}_{2,1} & \beta_1\hat{I}_{2,1} \\ \alpha_2\hat{I}_{2,2} & \beta_2\hat{I}_{2,2} \\ \vdots & \vdots \\ \alpha_P\hat{I}_{2,P} & \beta_P\hat{I}_{2,P} \end{matrix} &
\begin{matrix} -\alpha_1\hat{I}_{1,1} & -\beta_1\hat{I}_{1,1} \\ -\alpha_2\hat{I}_{1,2} & -\beta_2\hat{I}_{1,2} \\ \vdots & \vdots \\ -\alpha_P\hat{I}_{1,P} & -\beta_P\hat{I}_{1,P} \end{matrix} &
\mathbf{0} & \cdots & \mathbf{0} \\
\begin{matrix} \alpha_1\hat{I}_{3,1} & \beta_1\hat{I}_{3,1} \\ \alpha_2\hat{I}_{3,2} & \beta_2\hat{I}_{3,2} \\ \vdots & \vdots \\ \alpha_P\hat{I}_{3,P} & \beta_P\hat{I}_{3,P} \end{matrix} &
\mathbf{0} &
\begin{matrix} -\alpha_1\hat{I}_{1,1} & -\beta_1\hat{I}_{1,1} \\ -\alpha_2\hat{I}_{1,2} & -\beta_2\hat{I}_{1,2} \\ \vdots & \vdots \\ -\alpha_P\hat{I}_{1,P} & -\beta_P\hat{I}_{1,P} \end{matrix} &
\cdots & \mathbf{0} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
\begin{matrix} \alpha_1\hat{I}_{K,1} & \beta_1\hat{I}_{K,1} \\ \alpha_2\hat{I}_{K,2} & \beta_2\hat{I}_{K,2} \\ \vdots & \vdots \\ \alpha_P\hat{I}_{K,P} & \beta_P\hat{I}_{K,P} \end{matrix} &
\mathbf{0} & \mathbf{0} & \cdots &
\begin{matrix} -\alpha_1\hat{I}_{1,1} & -\beta_1\hat{I}_{1,1} \\ -\alpha_2\hat{I}_{1,2} & -\beta_2\hat{I}_{1,2} \\ \vdots & \vdots \\ -\alpha_P\hat{I}_{1,P} & -\beta_P\hat{I}_{1,P} \end{matrix}
\end{bmatrix}
\begin{bmatrix} \cos\phi_1 \\ \sin\phi_1 \\ \vdots \\ \cos\phi_K \\ \sin\phi_K \end{bmatrix}
$$

Method



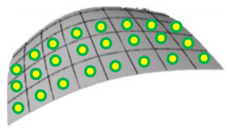
$$
\begin{bmatrix} \hat{I}_{1,1} - \hat{I}_{2,1} \\ \vdots \\ \hat{I}_{1,P} - \hat{I}_{2,P} \\ \vdots \\ \hat{I}_{1,1} - \hat{I}_{K,1} \\ \vdots \\ \hat{I}_{1,P} - \hat{I}_{K,P} \end{bmatrix}
=
\begin{bmatrix}
\begin{matrix} \alpha_1 \hat{I}_{2,1} & \beta_1 \hat{I}_{2,1} \\ \alpha_2 \hat{I}_{2,2} & \beta_2 \hat{I}_{2,2} \\ \vdots & \vdots \\ \alpha_P \hat{I}_{2,P} & \beta_P \hat{I}_{2,P} \end{matrix} &
\begin{matrix} -\alpha_1 \hat{I}_{1,1} & -\beta_1 \hat{I}_{1,1} \\ -\alpha_2 \hat{I}_{1,2} & -\beta_2 \hat{I}_{1,2} \\ \vdots & \vdots \\ -\alpha_P \hat{I}_{1,P} & -\beta_P \hat{I}_{1,P} \end{matrix} &
\mathbf{0} & \cdots & \mathbf{0} \\
\begin{matrix} \alpha_1 \hat{I}_{3,1} & \beta_1 \hat{I}_{3,1} \\ \alpha_2 \hat{I}_{3,2} & \beta_2 \hat{I}_{3,2} \\ \vdots & \vdots \\ \alpha_P \hat{I}_{3,P} & \beta_P \hat{I}_{3,P} \end{matrix} &
\mathbf{0} &
\begin{matrix} -\alpha_1 \hat{I}_{1,1} & -\beta_1 \hat{I}_{1,1} \\ -\alpha_2 \hat{I}_{1,2} & -\beta_2 \hat{I}_{1,2} \\ \vdots & \vdots \\ -\alpha_P \hat{I}_{1,P} & -\beta_P \hat{I}_{1,P} \end{matrix} &
\cdots & \mathbf{0} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
\begin{matrix} \alpha_1 \hat{I}_{K,1} & \beta_1 \hat{I}_{K,1} \\ \alpha_2 \hat{I}_{K,2} & \beta_2 \hat{I}_{K,2} \\ \vdots & \vdots \\ \alpha_P \hat{I}_{K,P} & \beta_P \hat{I}_{K,P} \end{matrix} &
\mathbf{0} & \mathbf{0} & \cdots &
\begin{matrix} -\alpha_1 \hat{I}_{1,1} & -\beta_1 \hat{I}_{1,1} \\ -\alpha_2 \hat{I}_{1,2} & -\beta_2 \hat{I}_{1,2} \\ \vdots & \vdots \\ -\alpha_P \hat{I}_{1,P} & -\beta_P \hat{I}_{1,P} \end{matrix}
\end{bmatrix}
\mathbf{P}
$$

Method



$$\mathbf{D} = \mathbf{O}\,\mathbf{P}$$

Method



$$\mathbf{D} = \mathbf{O}\mathbf{P}$$

$$\arg\min \|\mathbf{D} - \mathbf{O}\mathbf{P}\|$$

Solve linear system

$$\mathbf{P} = (\mathbf{O}^T\mathbf{O})^{-1}\mathbf{O}^T\mathbf{D}$$

Method

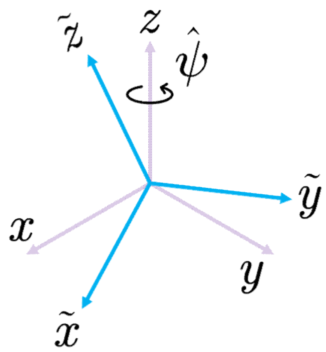
Radiometry

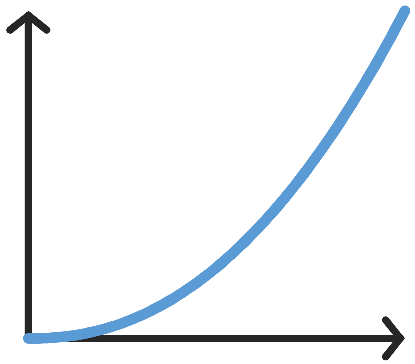
Geometry

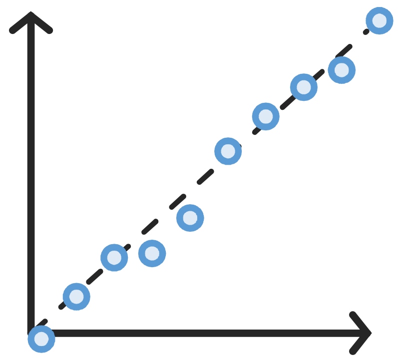
Polarimetry

$$\hat{g}(M_{k,p}) = t_p + a \cos 2\left(\phi_k - \hat{\psi}_p\right)$$

Method

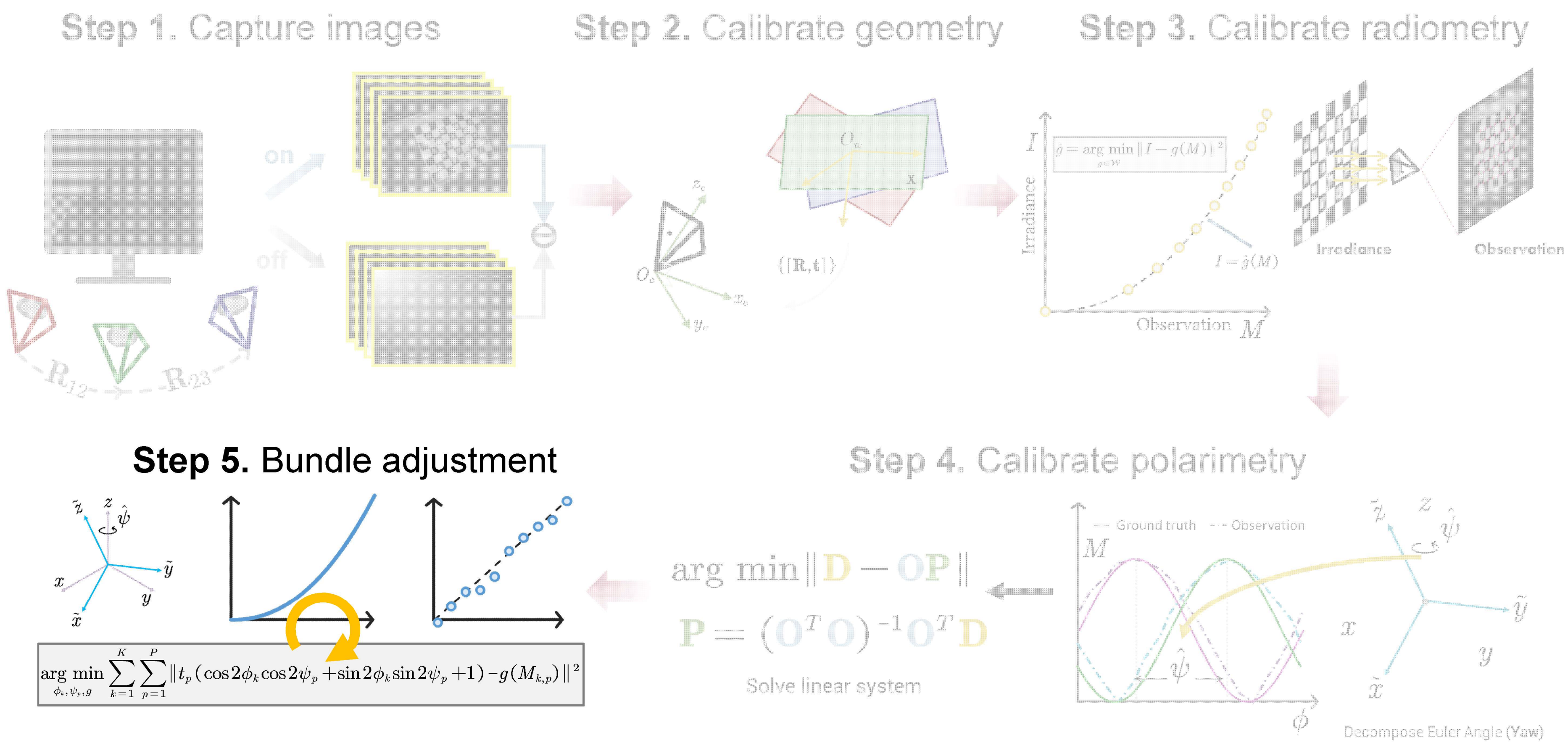




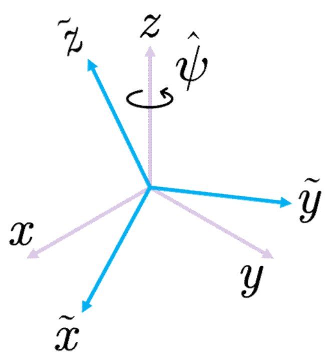


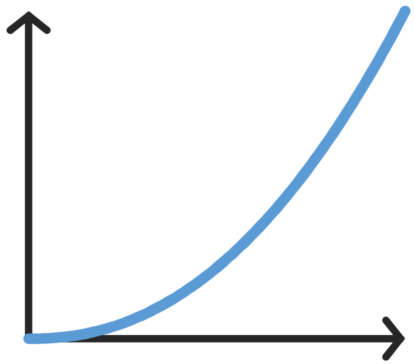
Method

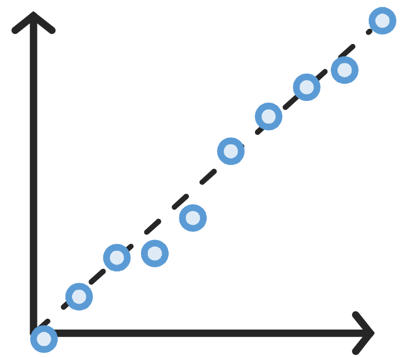
Overview



Method

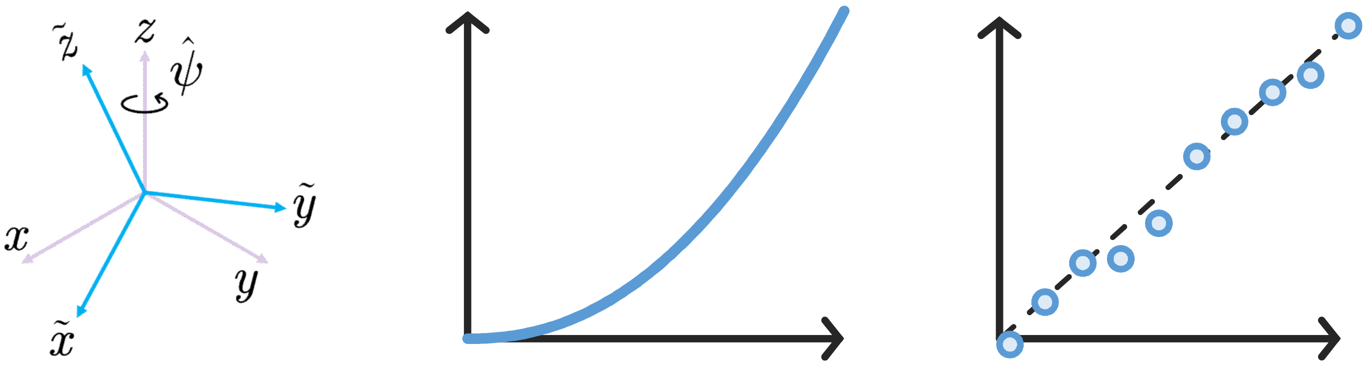






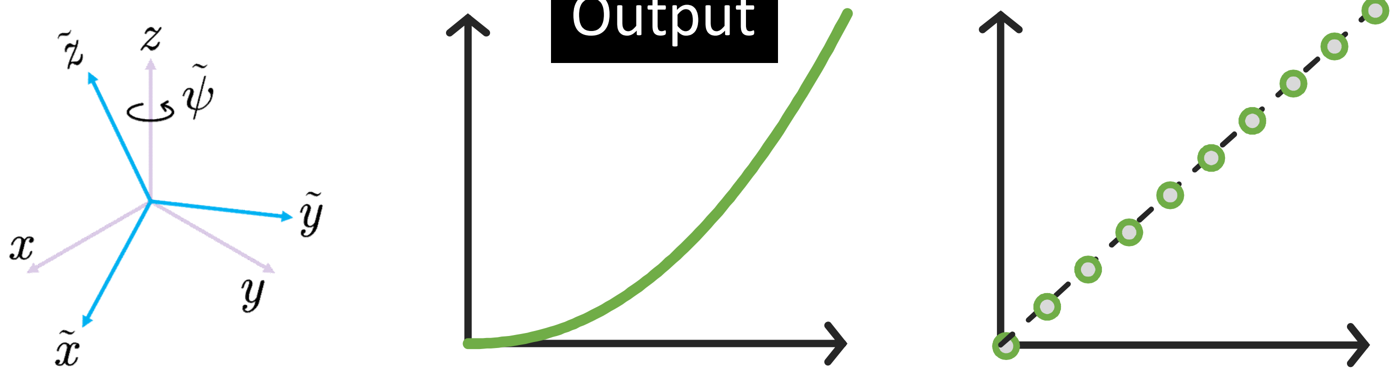
$$\arg\min_{\phi_k,\psi_p,g} \sum_{k=1}^{K} \sum_{p=1}^{P} \left\| t_p(\cos 2\phi_k \cos 2\psi_p + \sin 2\phi_k \sin 2\psi_p + 1) - g(M_{k,p}) \right\|^2$$

Method



$$\underset{\phi_k,\psi_p,g}{\arg\min} \sum_{k=1}^{K} \sum_{p=1}^{P} \| t_p(\cos 2\phi_k \cos 2\psi_p + \sin 2\phi_k \sin 2\psi_p + 1) - g(M_{k,p}) \|^2$$

Output



Method

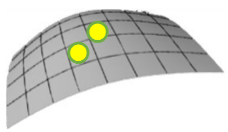
$$\boxed{\hat{g}(M_{k,p}) = t_p(1 + \alpha_p \cos 2\phi_k + \beta_p \sin 2\phi_k)}$$

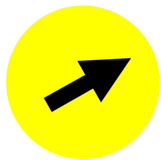
KP data $\geq$ *P+K unknown*

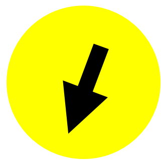
Method

$$\boxed{\hat{g}(M_{k,p}) = t_p(1 + \alpha_p \cos 2\phi_k + \beta_p \sin 2\phi_k)}$$

$$KP\ data \quad \geq \quad P{+}K\ unknown$$





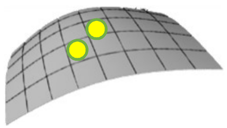


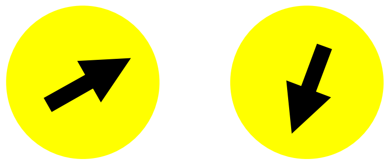
At least
- 2 object points
- 2 polarizing channels

Method

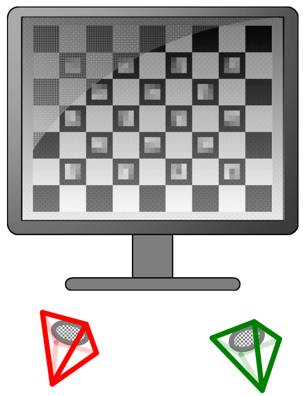
$$\hat{g}(M_{k,p}) = t_p(1 + \alpha_p \cos 2\phi_k + \beta_p \sin 2\phi_k)$$

$$KP \text{ data} \quad \geq \quad P{+}K \text{ unknown}$$





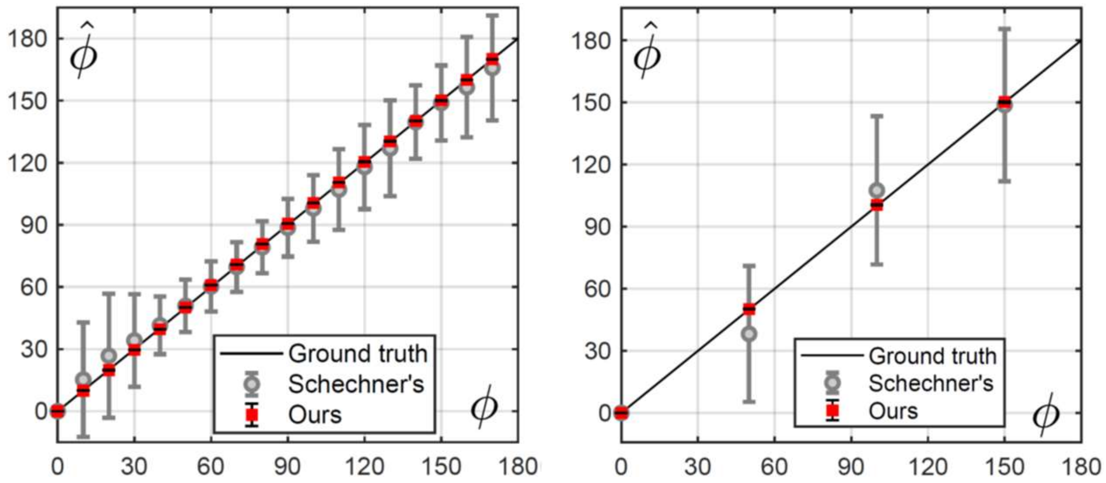
At least
- 2 object points
- 2 polarizing channels



At least
- rotate once in the polarizer plane

Experiments – Simulation

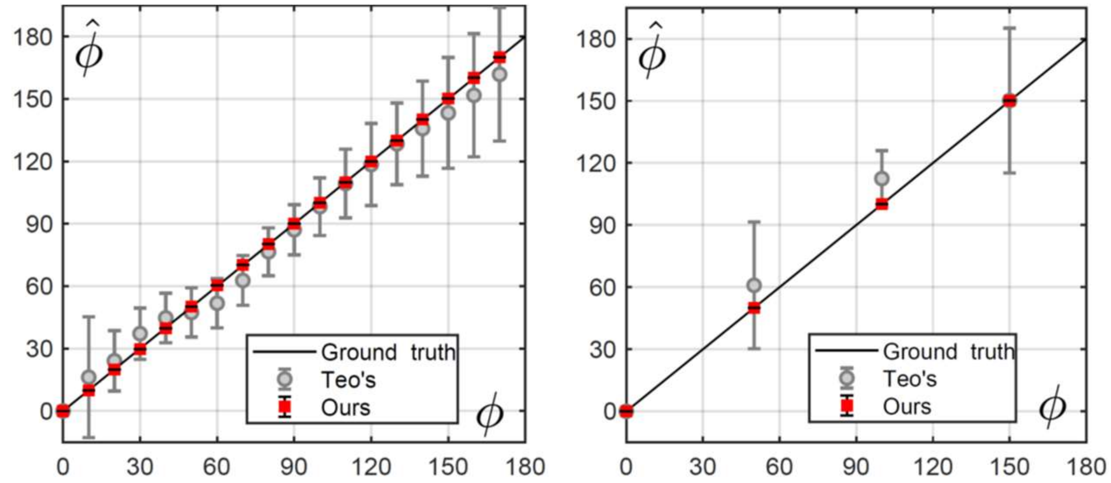
Known CRF



1. Our method performs well
2. Schechner’s method is sensitive to initialization
3. Schechner’s method is less reliable when # phi is small, but our method is still robust

Experiments – Simulation

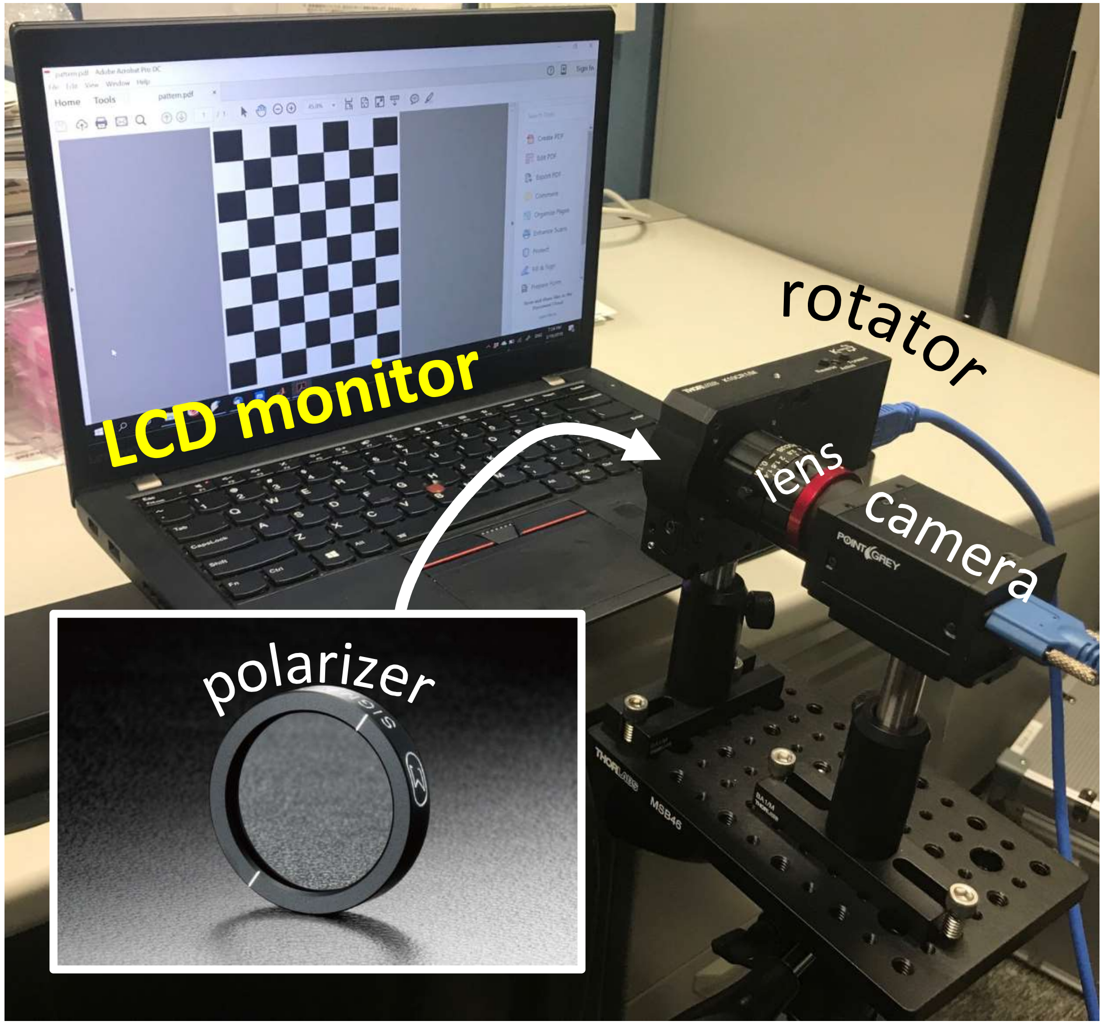
Unknown CRF



1. Our method performs well
2. Teo's method is sensitive to initialization
3. Teo's method is less reliable when # phi is small, but our method is still robust

Experiments – Real-world

Setup



Experiments – Real-world

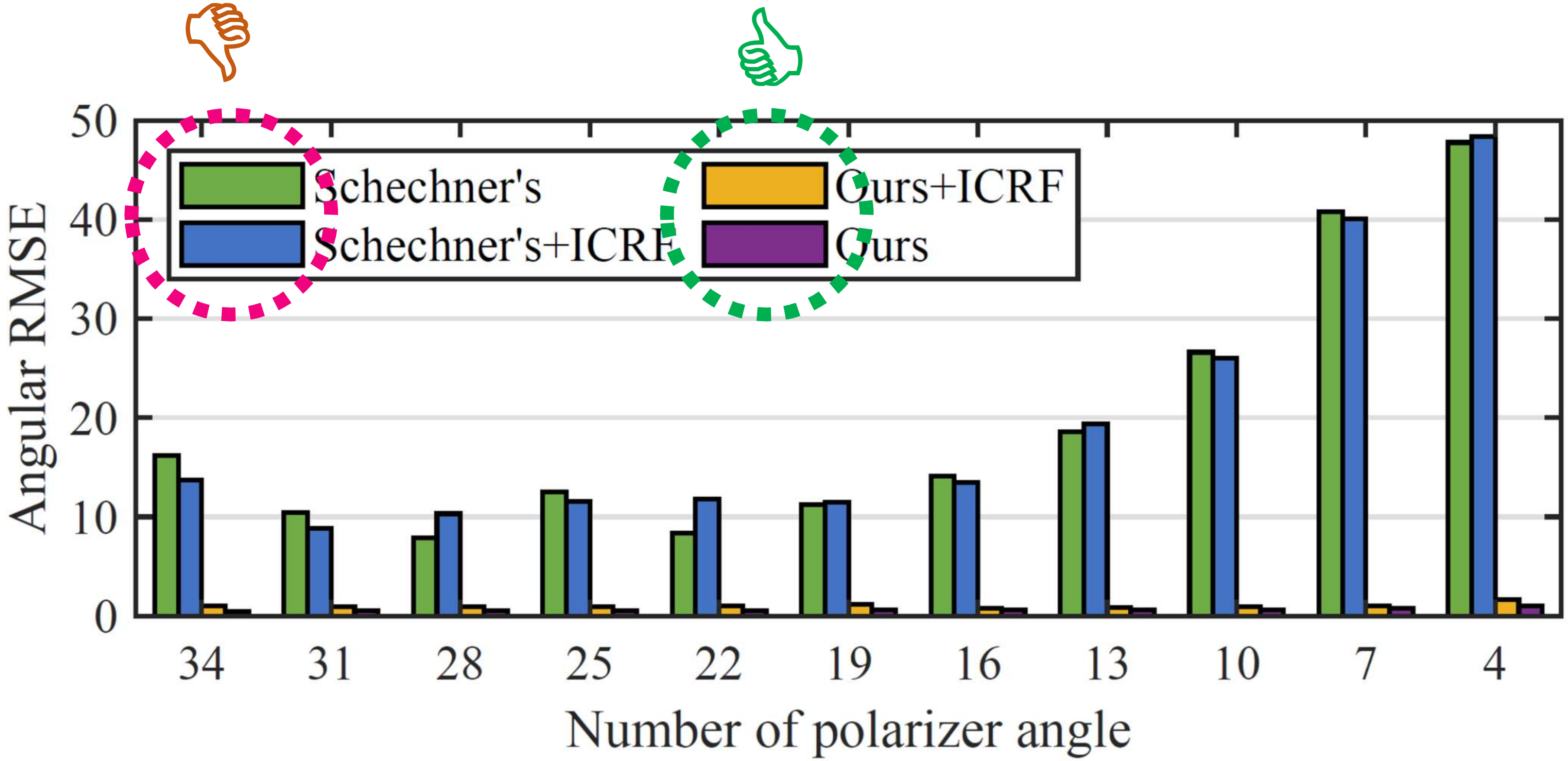
Environment illumination

	Known ICRF		Unknown ICRF	
	CRF err.	Ang. err.	CRF err.	Ang. err.
Dark room	✗	0.76 ± 0.20	0.01 ± 0.01	$\mathbf{0.48 \pm 0.15}$
Bright room	✗	0.80 ± 0.28	0.05 ± 0.01	$\mathbf{0.71 \pm 0.11}$

- Reliably remove effect of environmental illumination
- The given ICRF could contain errors, but our joint method is good

Experiments – Real-world

Effectiveness of using less polarizer angles



Experiments – Real-world

Benefits of the adapted checker pattern P3

	Known ICRF			Unknown ICRF		
	CRF err.	Ang. err.	#images	CRF err.	Ang. err.	#images
P0	✗	$\boxed{0.80\pm0.16}$	≥ 4	0.20 ± 0.06	82.2 ± 26.1	≥ 4
P1	✗	0.78 ± 0.15	≥ 4	0.07 ± 0.02	1.24 ± 0.43	≥ 4
P2	✗	0.79 ± 0.14	≥ 4	0.02 ± 0.02	$\mathbf{0.38\pm0.32}$	$\geq 4{+}11$
P3	✗	0.78 ± 0.15	≥ 4	$\mathbf{0.01\pm0.01}$	0.48 ± 0.15	≥ 4

- **known ICRF**: standard checker pattern can achieve the same accuracy

- **unknown ICRF**: P1 suffers from *spatial inconsistency*
- **unknown ICRF**: more accurate but require more images
- **unknown ICRF**: our results is close to GT with less images

Experiments – Real-world

Benefits of the adapted checker pattern P3

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P3	✗	0.78 ± 0.15	≥ 4	$\mathbf{0.01 \pm 0.01}$	0.48 ± 0.15	≥ 4

- Accurate estimated ICRF could be distorted during BA

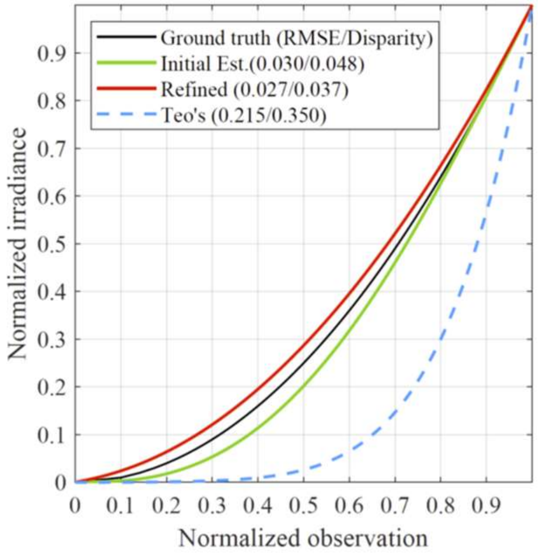
Experiments – Real-world

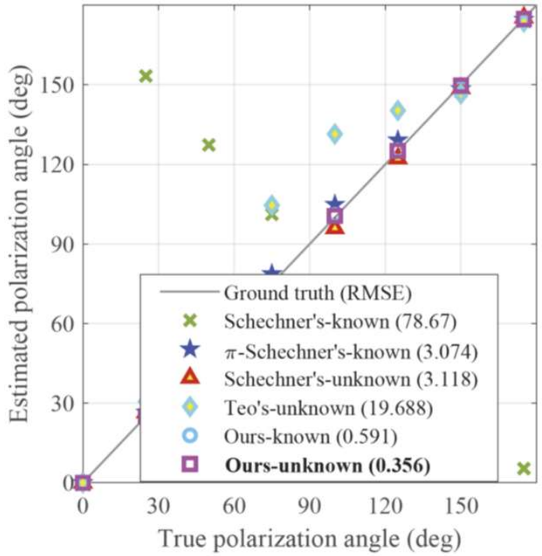
Joint calibration *vs.* separate calibration

	Known ICRF				Unknown ICRF			
	CRF err.	Ang. err.	ψ err.	#images	CRF err.	Ang. err.	ψ err.	#images
Separate	✗	0.45	3.08	$\geq 4+2$	0.02	0.83	3.10	$\geq 4+2+11$
Joint	0.02	$\mathbf{0.38}$	$\mathbf{0.19}$	$\geq \mathbf{4}$	$\mathbf{0.01}$	$\mathbf{0.48}$	$\mathbf{0.20}$	$\geq \mathbf{4}$

Experiments – Real-world

Comparison with the state-of-the-art methods





CRF	Method	CRF err.	Ang. err.	#polar. ang.	#images
known	[2]	✗	8.85 ± 15.39	≥ 4	≥ 4
	Ours	✗	$\mathbf{0.62 \pm 0.28}$	$\geq \mathbf{2}$	≥ 4
unknown	[2] + ICRF	✗	15.84 ± 29.59	≥ 4	$\geq 4+11$
	[3]	0.13 ± 0.09	12.56 ± 7.31	≥ 4	≥ 4
	Ours	$\mathbf{0.04 \pm 0.02}$	$\mathbf{0.63 \pm 0.18}$	$\geq \mathbf{2}$	≥ 4

Experiments – Real-world

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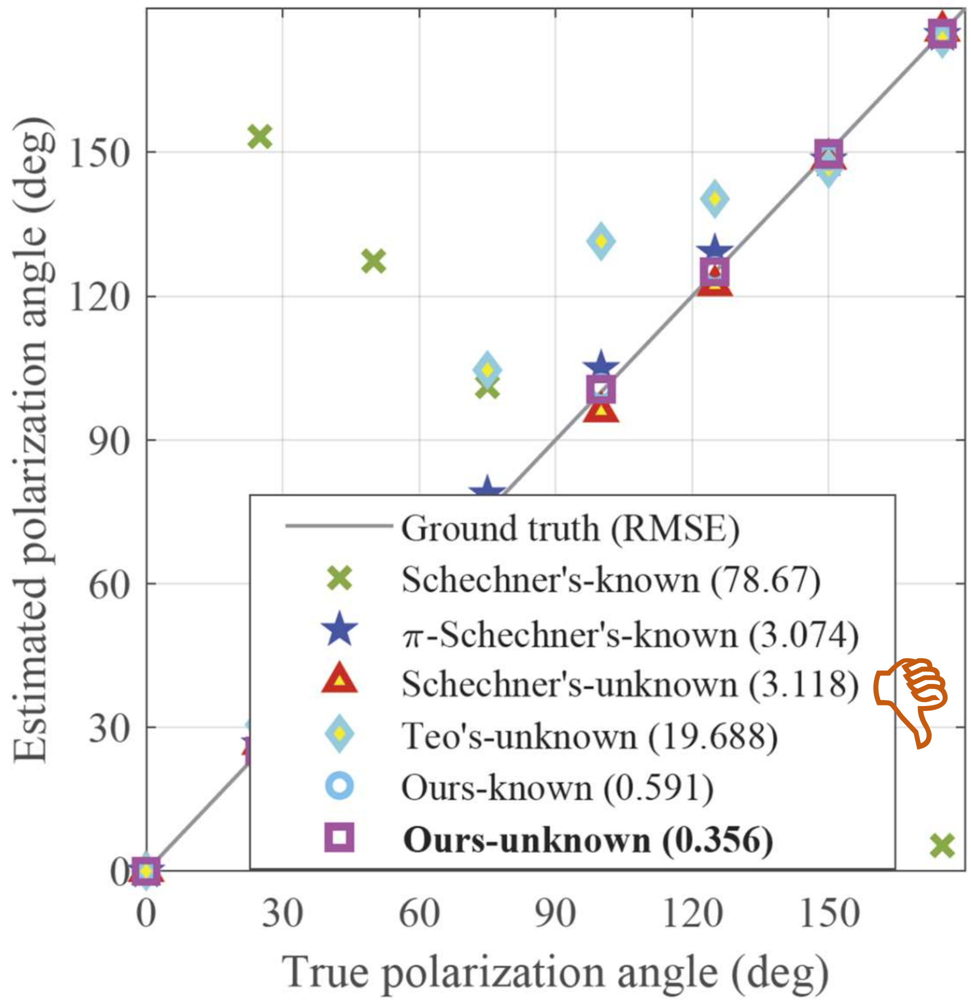
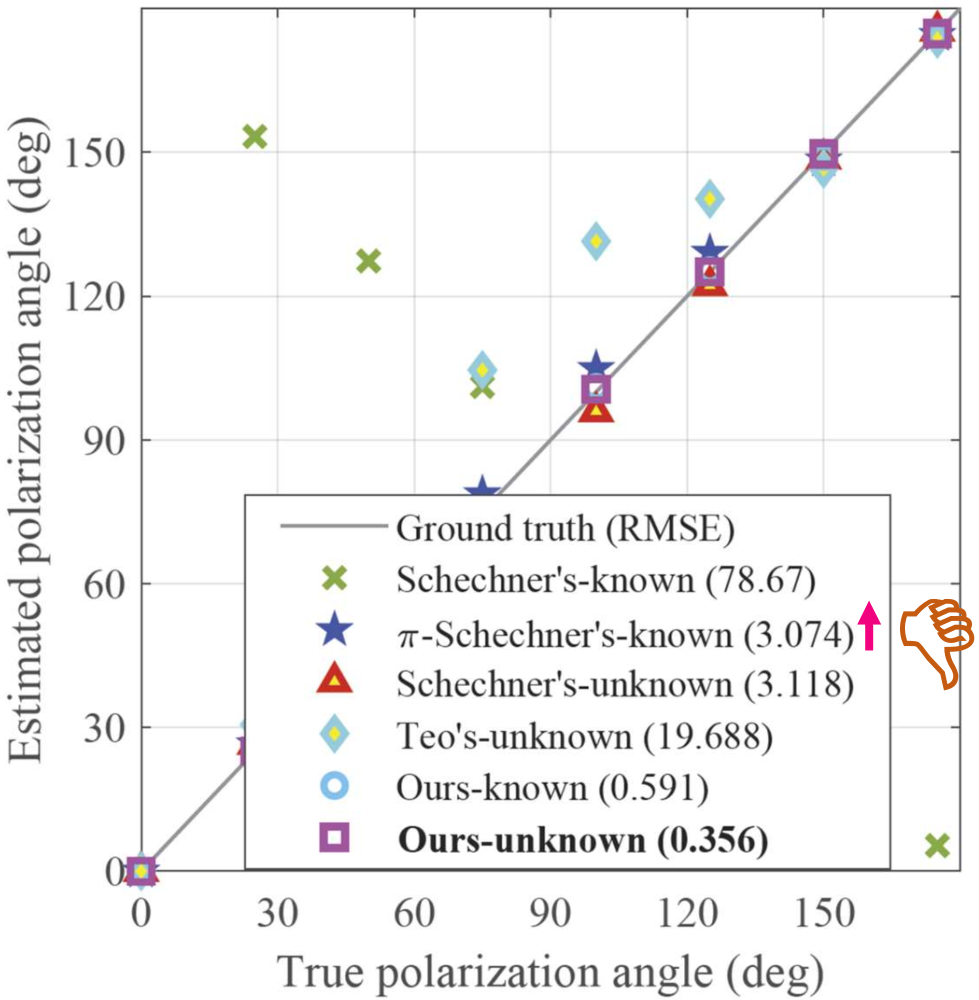


Experiments – Real-world

Comparison with the state-of-the-art methods



Experiments – Real-world

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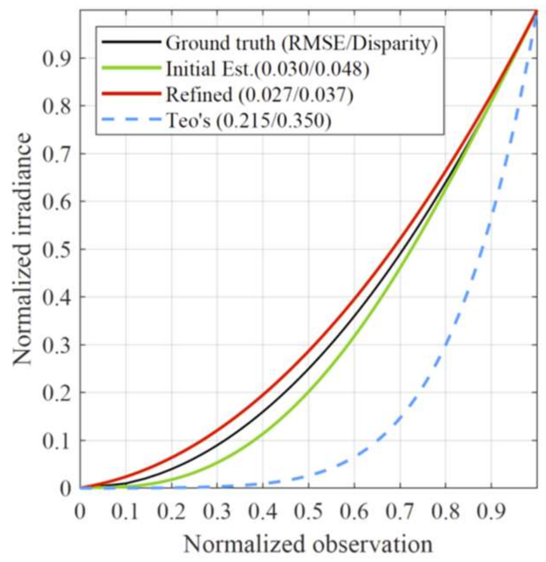

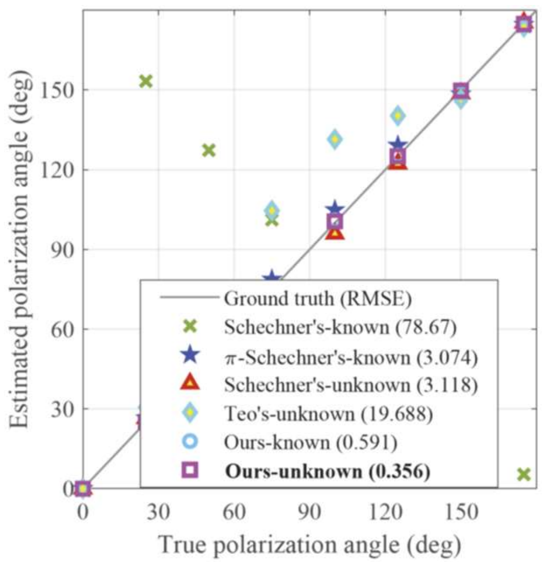

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Experiments – Real-world

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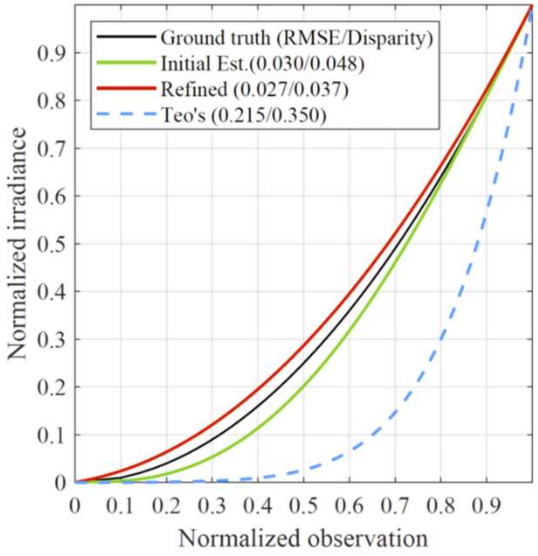

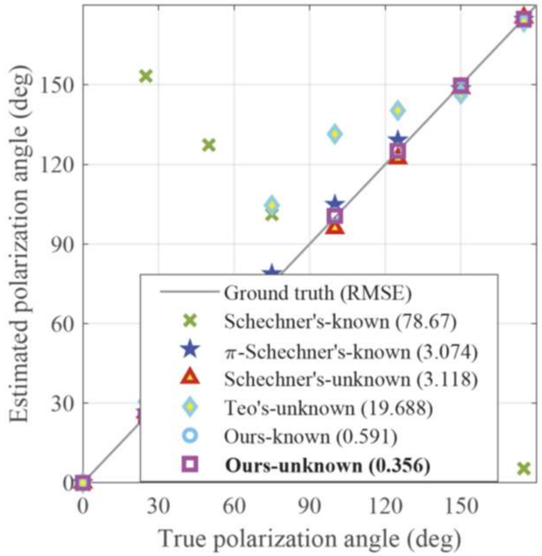

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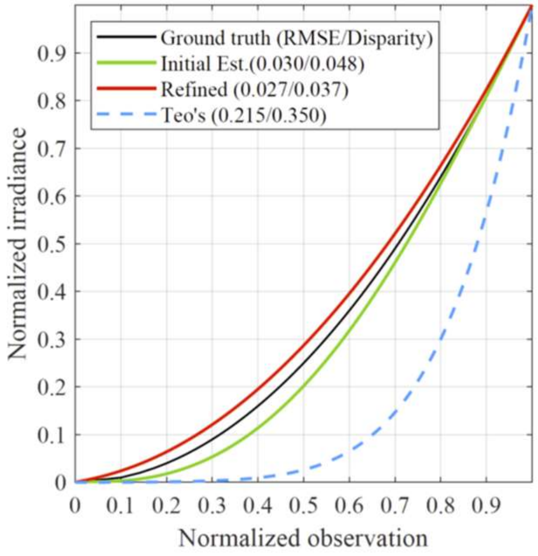
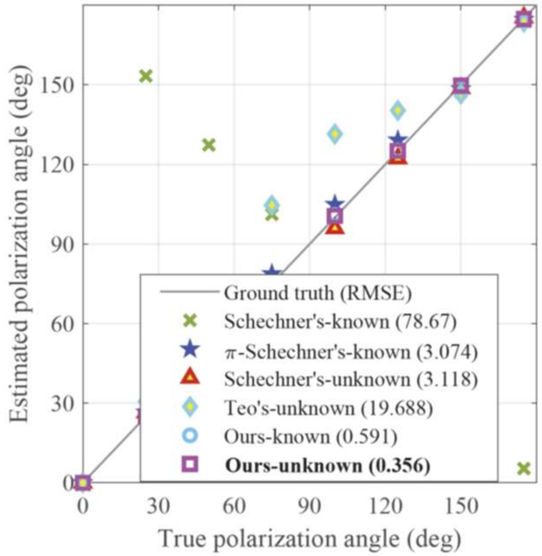
Experiments – Real-world

Comparison with the state-of-the-art methods





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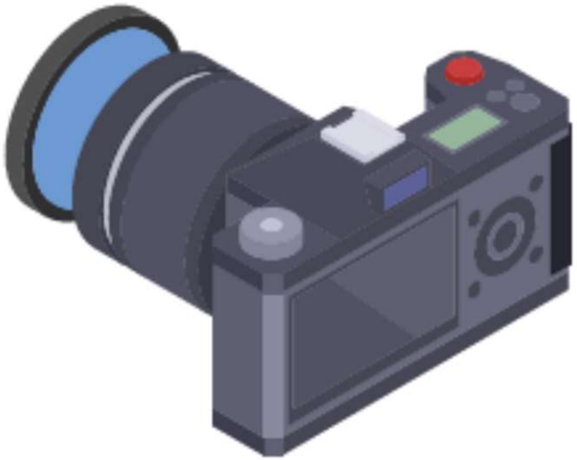
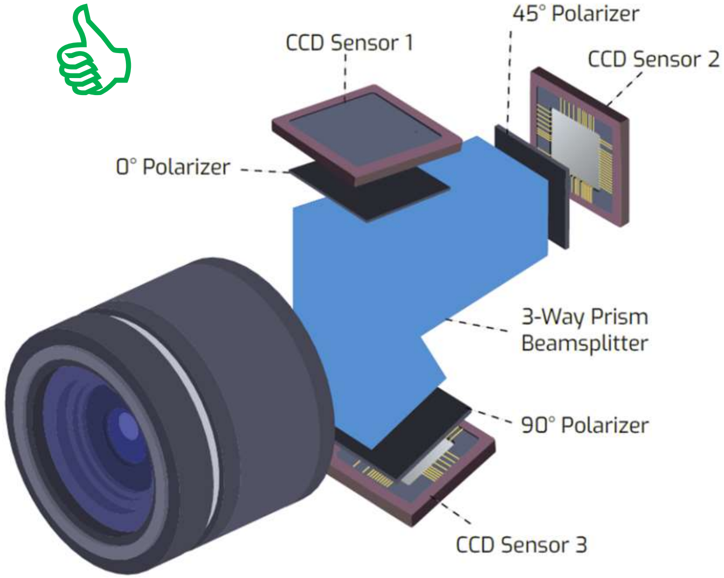
Discussion

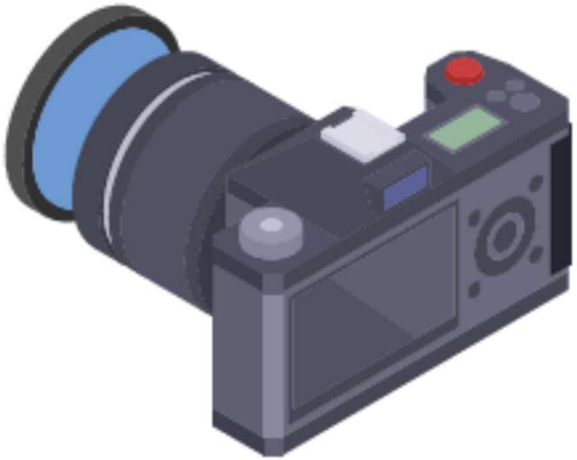
Applicability

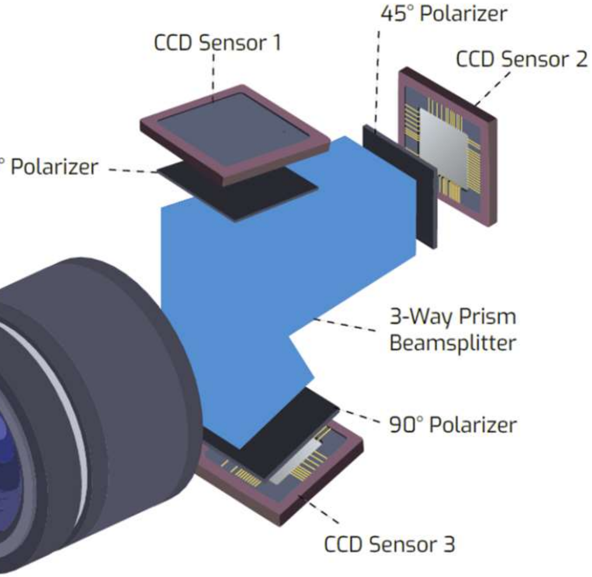


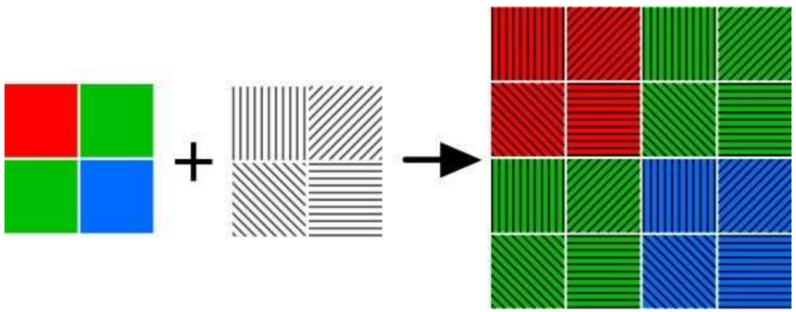


Discussion

Applicability

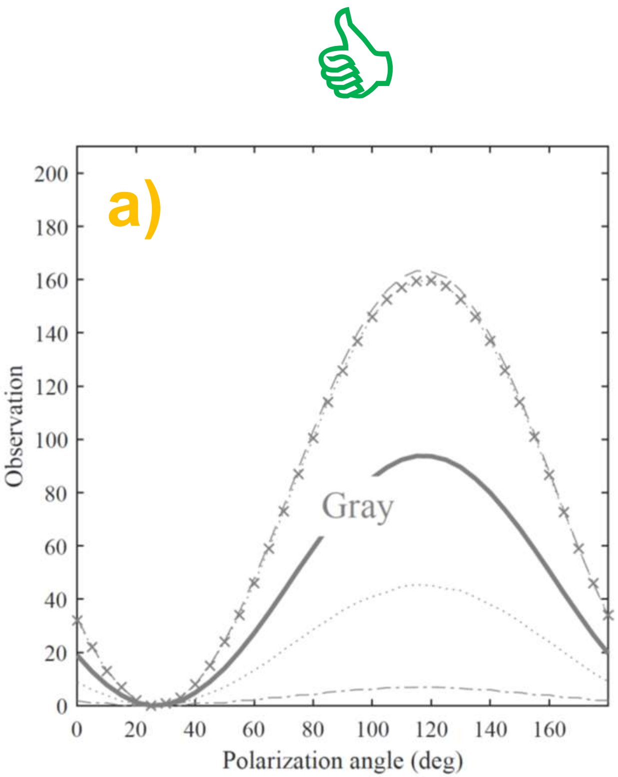




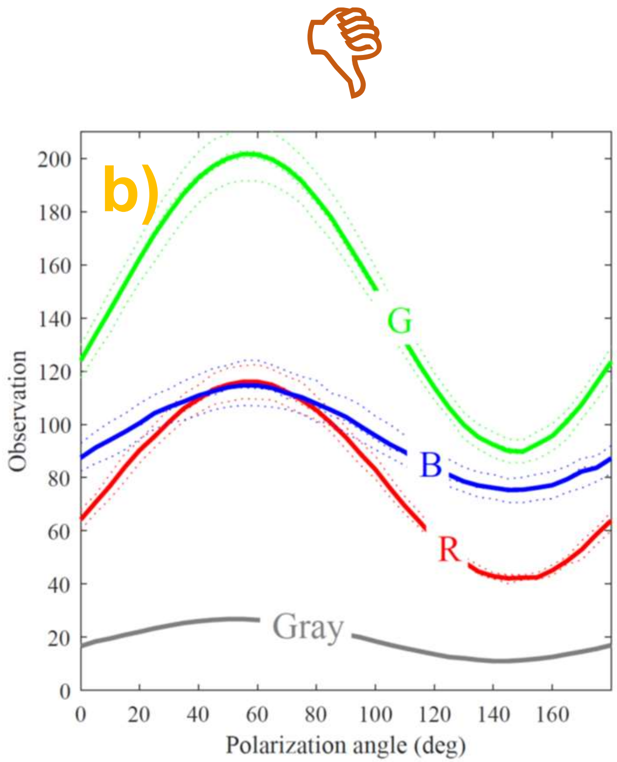


Discussion

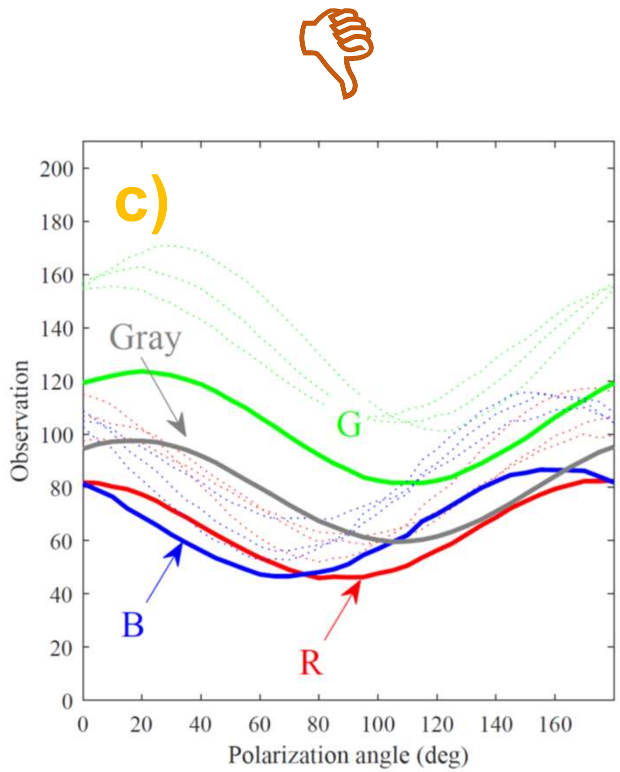
LCD screens with a touch panel



HUAWEI Meta 10 Lite

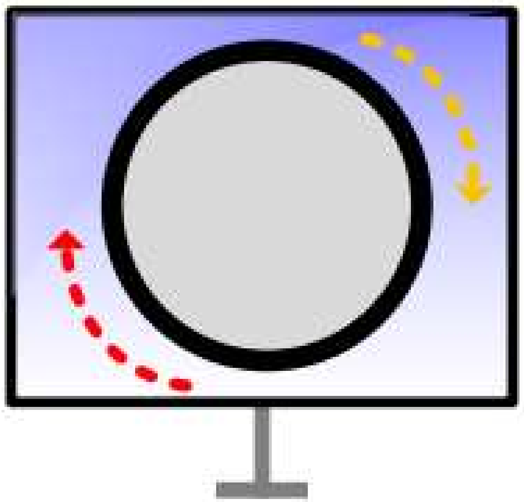


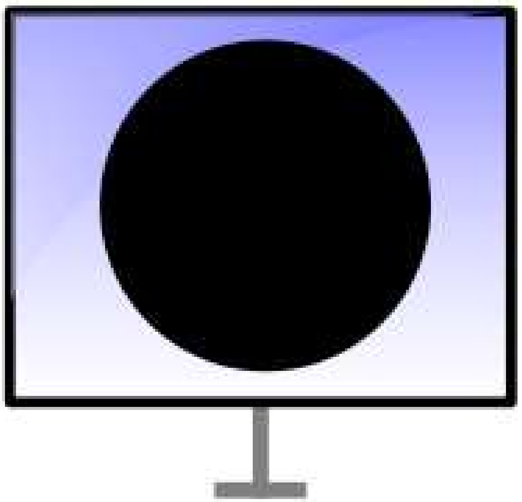
iPhone 6s

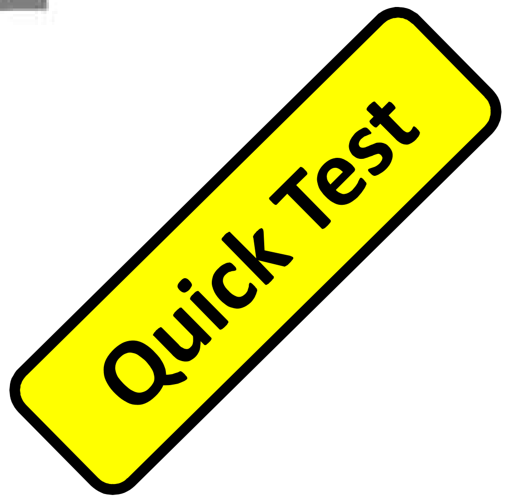


iPhone 7 Plus

Discussion







Conclusion

We propose a *joint* calibration method using characteristics of an LCD monitor.

- **Novel and new:** The basic idea of joint calibration with an LCD monitor is novel, and our linear polarization calibration method due to the characteristics of LCD monitors is new.
- **Efficient and effective:** Using the estimated CRF as initialization, our bundle adjustment leads to accurate and reliable results. Which is demonstrated by conducting extensive experiments. Considering that LCD monitors are everywhere, we believe that our method is easy to use as self-calibration methods.

Thank you!