Monochrome and Color Polarization Demosaicking Using Edge-Aware Residual Interpolation

Miki Morimatsu, Yusuke Monno, Masayuki Tanaka, and Masatoshi Okutomi
Tokyo Institute of Technology, Tokyo, Japan

Session: ELI-01 Electronic Imaging
ICIP2020

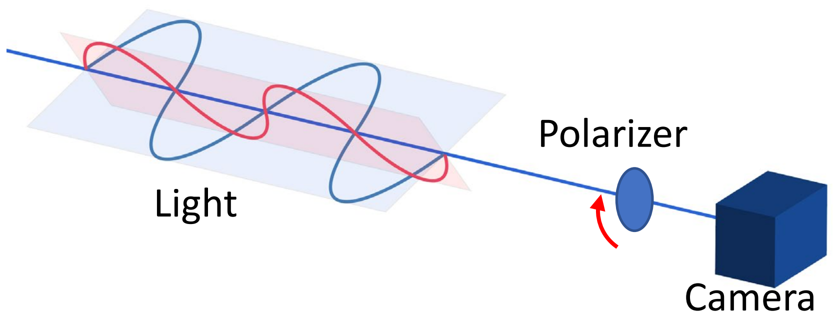
Background

Polarization

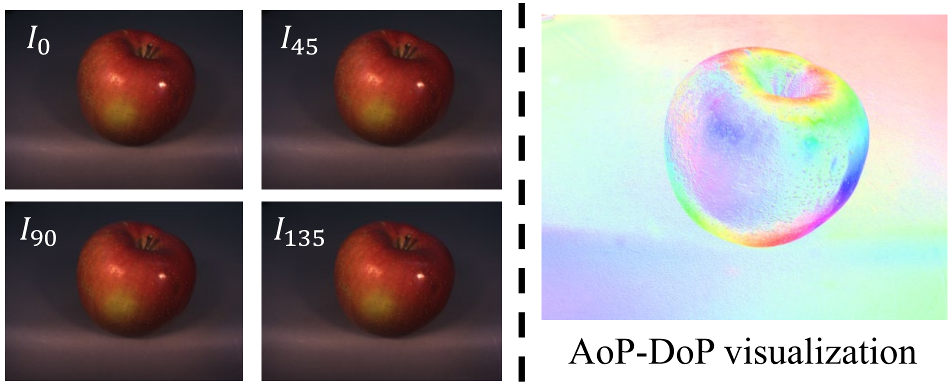
- Physical property of electromagnetic wave

Polarization image

- Set of images obtained using a linear polarizer with different orientations



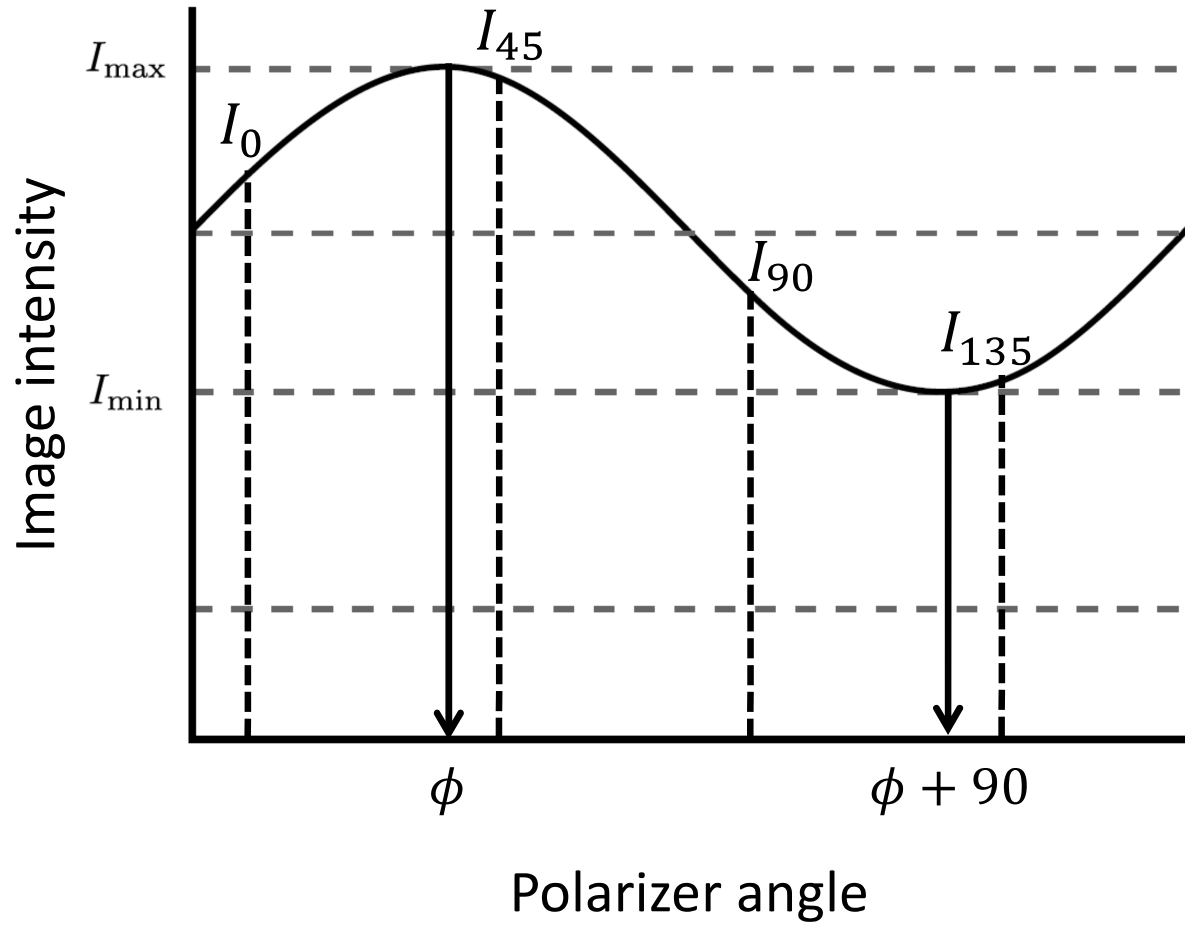
Polarization image acquisition



Polarization image

Background

Polarization model



Stokes vector

$$\boldsymbol{s} = \begin{bmatrix} s_0 \\ s_1 \\ s_2 \\ s_3 \end{bmatrix} = \begin{bmatrix} I_{max} + I_{min} \\ (I_{max} - I_{min})\cos(2\phi) \\ (I_{max} - I_{min})\sin(2\phi) \\ 0 \end{bmatrix} = \begin{bmatrix} I_0 + I_{90} \\ I_0 - I_{90} \\ I_{45} - I_{135} \\ 0 \end{bmatrix}$$

Intensity ($\boldsymbol{I}$)

$$I = I_{max} + I_{min} = s_0$$

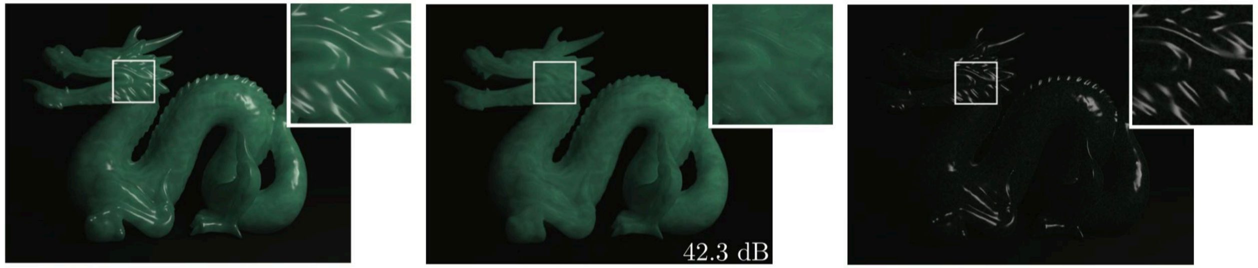
Degree of linear polarization (DoP: $\boldsymbol{\rho}$)

$$\rho = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} = \frac{\sqrt{s_1^2 + s_2^2}}{s_0}$$

Angle of linear polarization (AoP: $\boldsymbol{\phi}$)

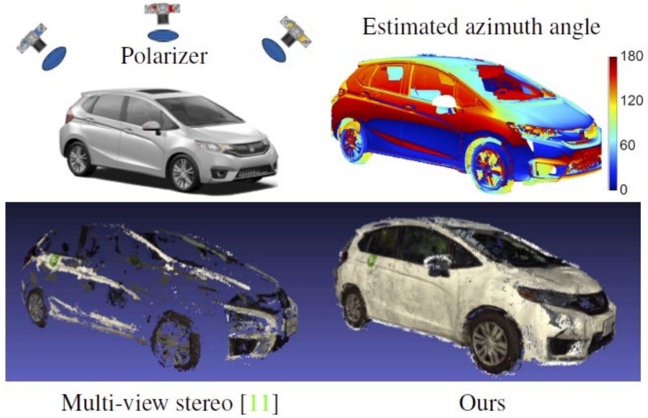
$$\phi = \frac{1}{2}\tan^{-1}\frac{s_2}{s_1}$$

Background: Applications

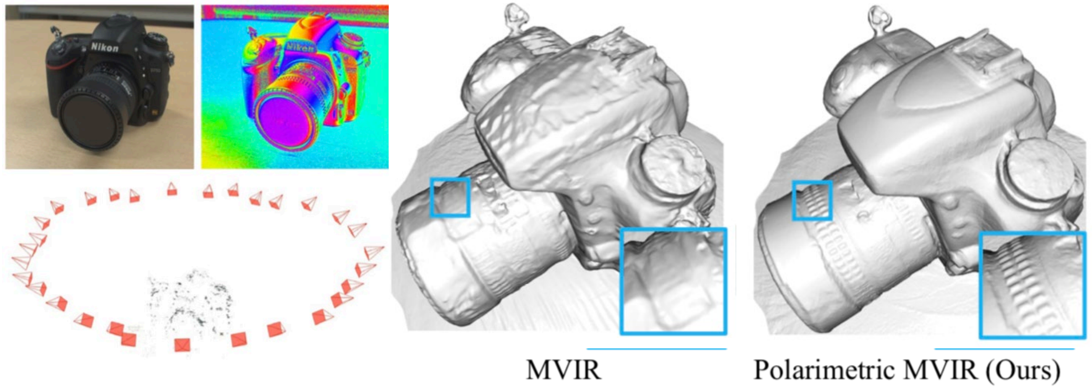


Specular removal [1]

Reflection separation [2]



Polarimetric multi-view stereo [3]



Polarimetric multi-view inverse rendering [4]

[1] L V. Jospin et al. “Embedded polarizing filters to separate diffuse and specular reflection,” ACCV, 2018.
[2] P. Wieschollek et al. “Separating reflection and transmission images in the wild,” ECCV, 2018.
[3] Z. Cui et al. “Polarimetric multi-view stereo,” CVPR, 2017.
[4] J. Zhao, Y. Monno, M. Okutomi, “Polarimetric multi-view inverse rendering,” ECCV, 2020.

Background: Image Acquisition

- **Rotating polarizer**

  ○ Higher quality images

  ✕ Not applicable to dynamic scenes and videos

3CCD camera

Rotating polarizer

- **Polarization filter array (PFA)**

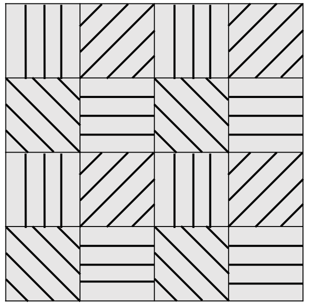
  ○ Dynamic scenes and videos

  ✕ Sparse mosaic data

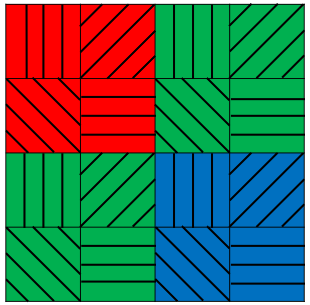
  ➡ **Need demosaicking**

Polarization camera

Monochrome PFA (MPFA)

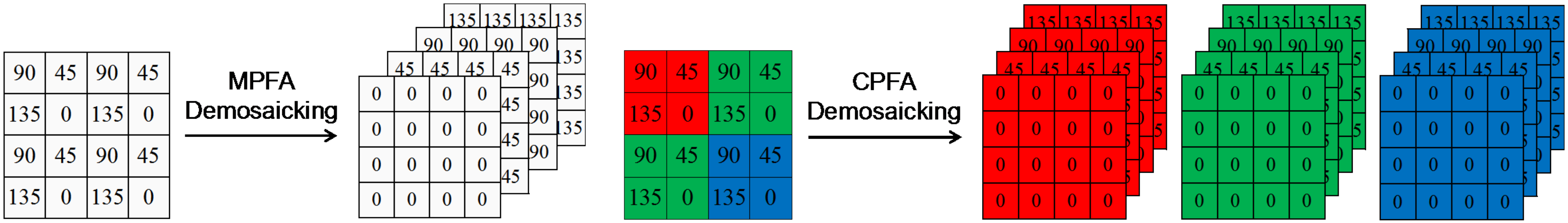


Color PFA (CPFA)



Our Contributions

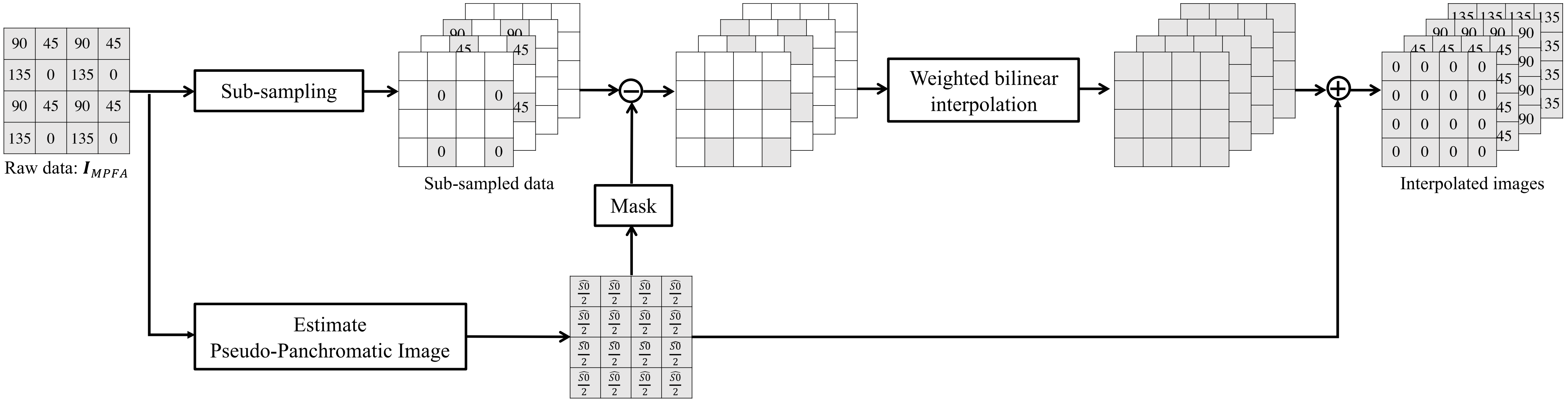
- Propose a **monochrome polarization filter array (MPFA) demosaicking** method based on edge-aware residual interpolation.
- Extend the proposed monochrome polarization demosaicking method to **color polarization filter array (CPFA) demosaicking.**
- Construct a **full 12-channel color-polarization image dataset**.



Existing MPFA Demosaicking Method

PPID [5]: Method based on pseudo-panchromatic image difference

- Demosaicking method based on a pseudo-panchromatic image
  (a guide image **not considering edge information**)



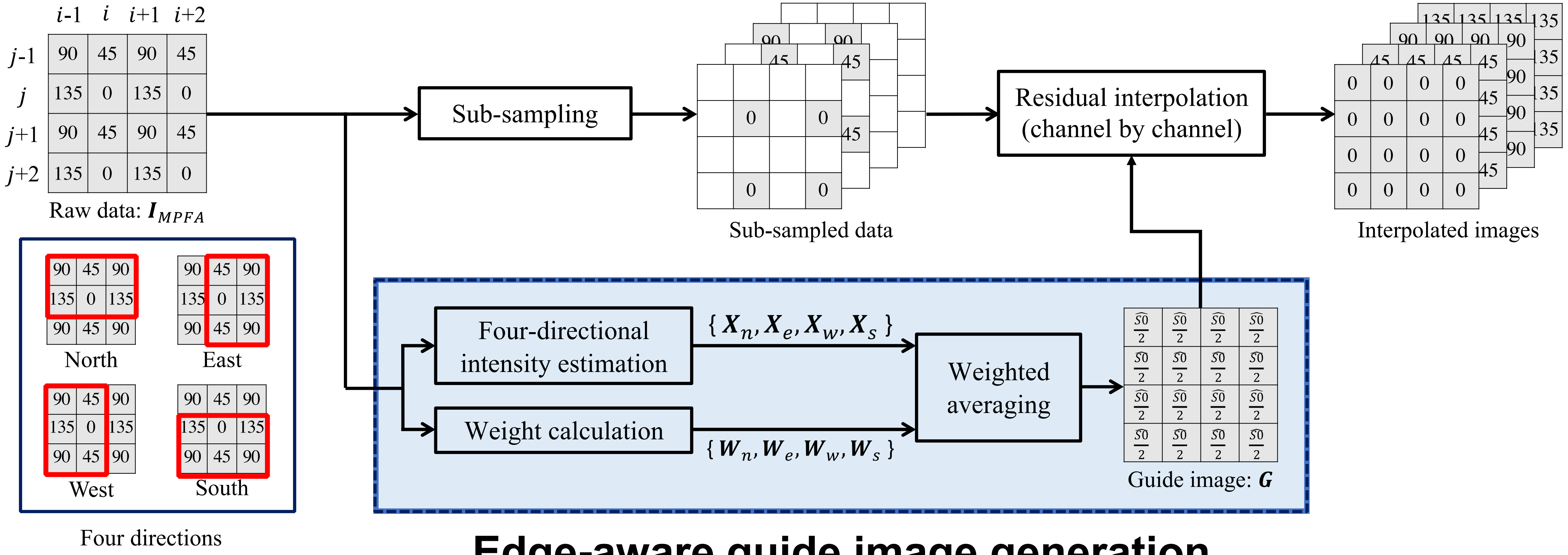
Guide image

[5] S. Mihoubi et al. "Survey of demosaicking methods for polarization filter array images," Sensors, 2018.

Proposed MPFA Demosaicking Method

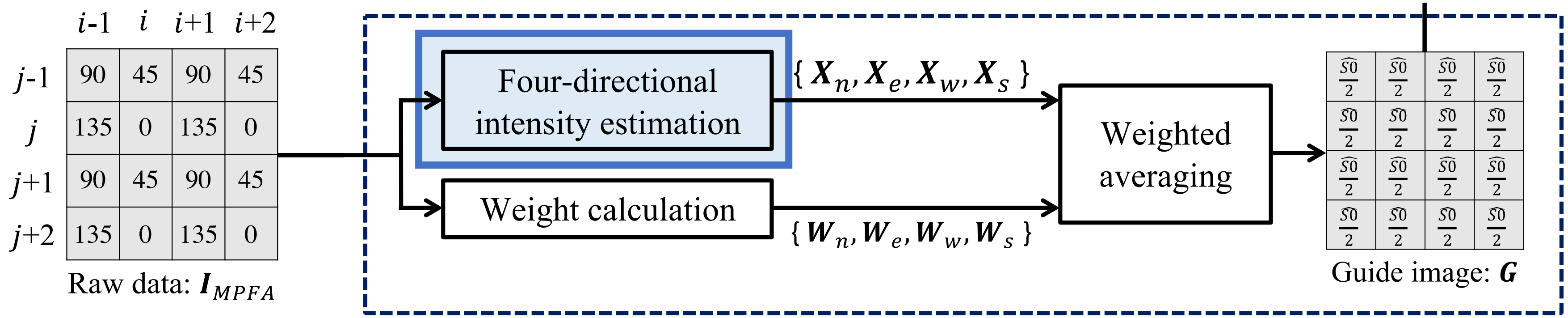
Edge-aware residual interpolation (EARI)

- Generate an edge-aware guide image

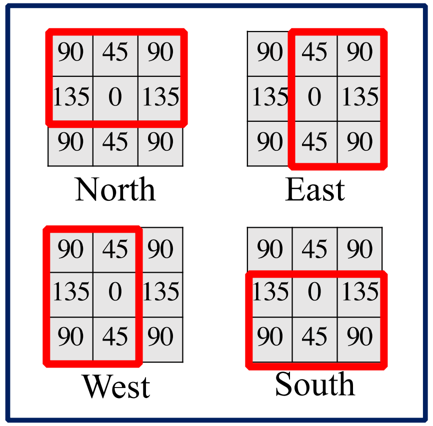


Edge-aware guide image generation

Edge-Aware Guide Image Generation



Edge-aware guide image generation

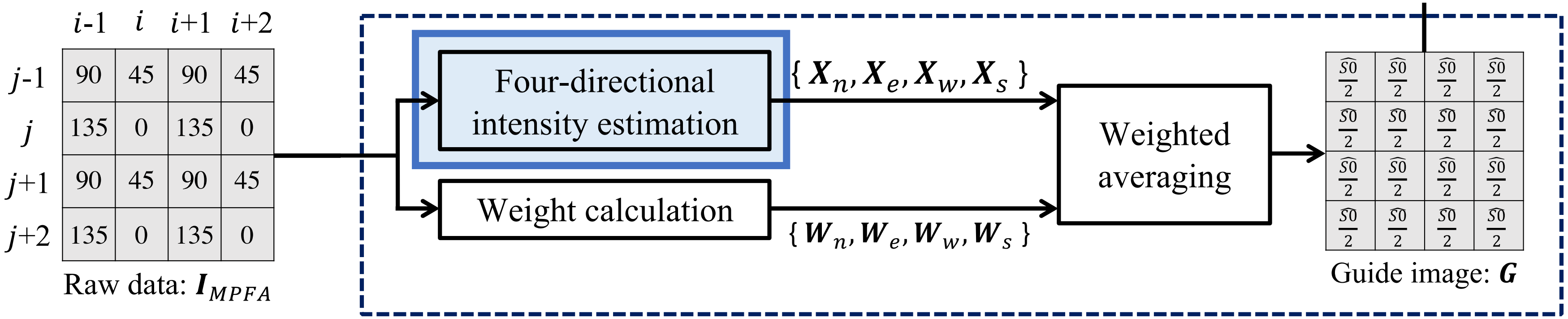


Four directions

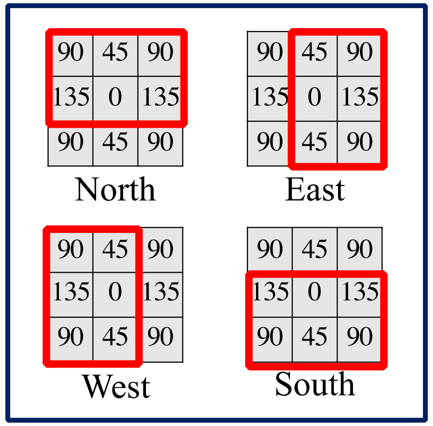
Four-directional intensity estimation

Intensity relationship : $S0 = I_0 + I_{90} = I_{45} + I_{135}$

Edge-Aware Guide Image Generation



Edge-aware guide image generation



Four directions

Four-directional intensity estimation

Intensity relationship : $S0 = I_0 + I_{90} = I_{45} + I_{135}$

Example of North direction

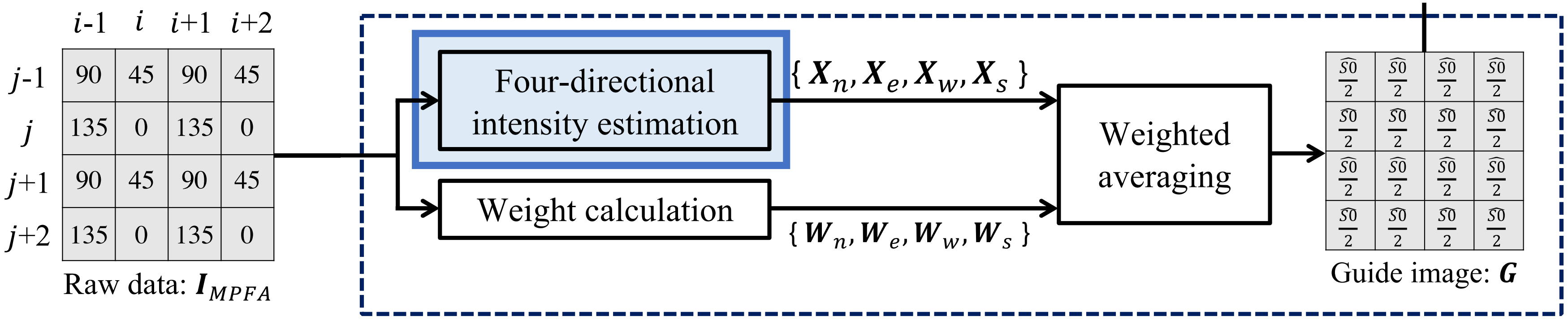
North direction

90	45	90
135	0	135
90	45	90

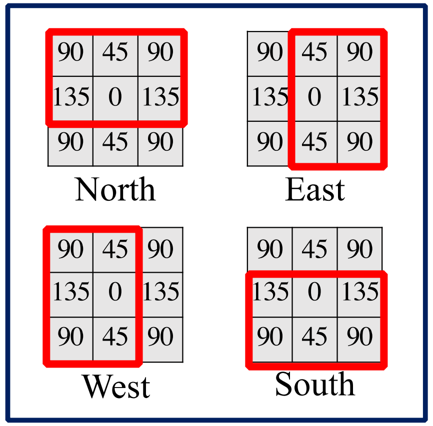
Estimated intensity using (I_0, I_{90})

$\widehat{S0}_{(0,90)} = \boldsymbol{I_0} + \boldsymbol{I_{90}}$

Edge-Aware Guide Image Generation



Edge-aware guide image generation



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Intensity relationship : $S0 = I_0 + I_{90} = I_{45} + I_{135}$

Example of North direction

North direction

90	**45**	**90**
135	**0**	**135**
90	**45**	**90**

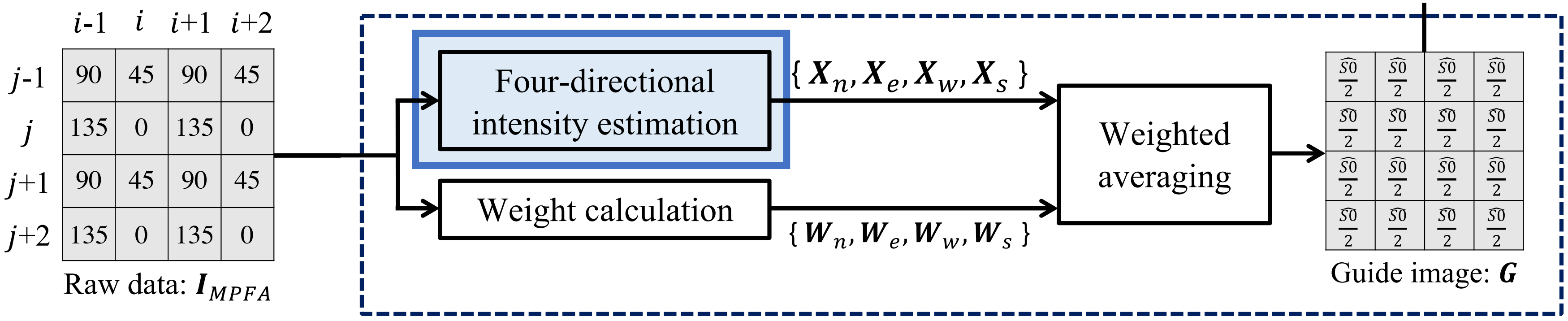
Estimated intensity using (I_0, I_{90})

$$\widehat{S0}_{(0,90)} = I_0 + I_{90}$$

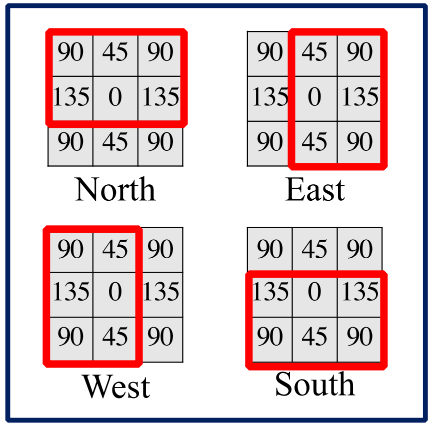
Estimated intensity using (I_{45}, I_{135})

$$\widehat{S0}_{(45,135)} = \boldsymbol{I_{45}} + \boldsymbol{I_{135}}$$

Edge-Aware Guide Image Generation



Edge-aware guide image generation



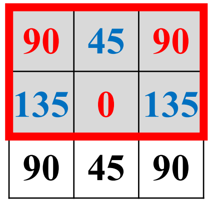
Four directions

Four-directional intensity estimation

Intensity relationship : $S0 = I_0 + I_{90} = I_{45} + I_{135}$

Example of North direction

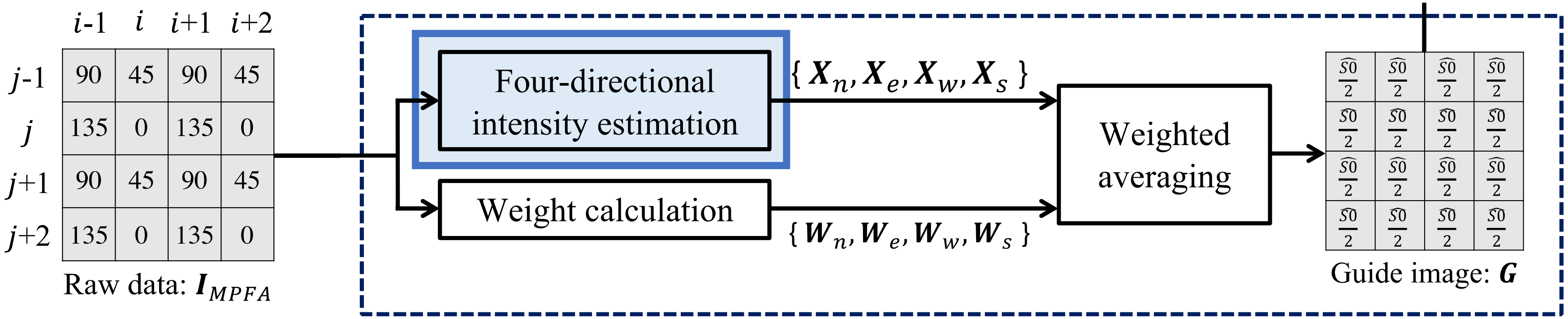
North direction



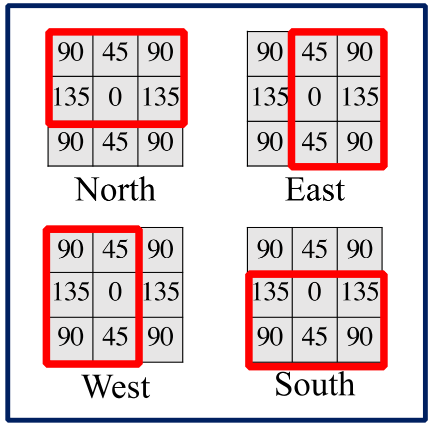
North direction intensity

$$\widehat{S0} = \frac{\widehat{S0}_{(0,90)} + \widehat{S0}_{(45,135)}}{2}$$

Edge-Aware Guide Image Generation



Edge-aware guide image generation



Four directions

Four-directional intensity estimation

Intensity relationship : $S0 = I_0 + I_{90} = I_{45} + I_{135}$

Example of North direction

North direction

90	45	90
135	0	135
90	45	90

North direction intensity

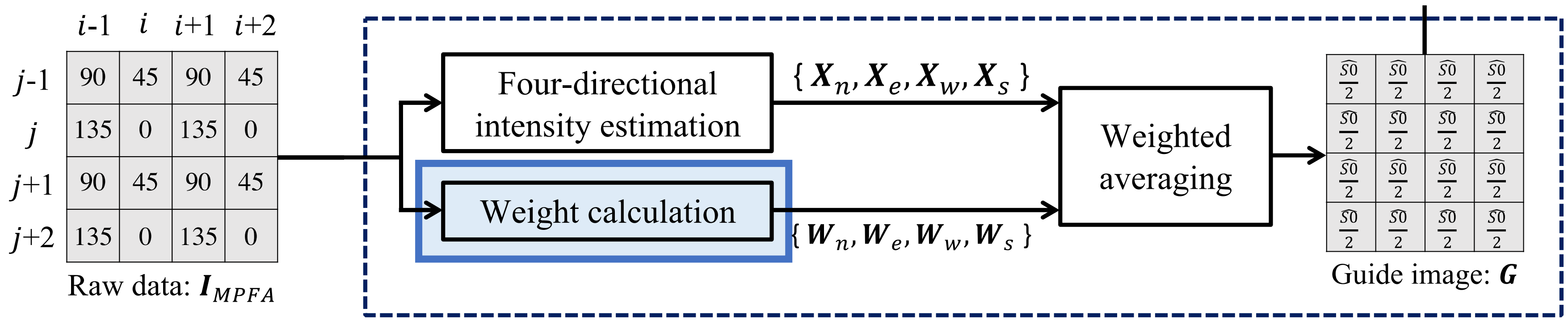
$$\widehat{S0} = \frac{\widehat{S0}_{(0,90)} + \widehat{S0}_{(45,135)}}{2}$$

Calculated by filtering

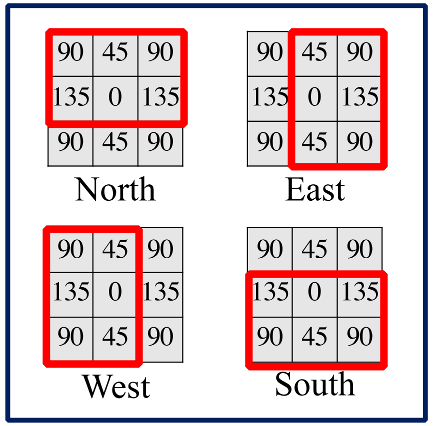
$$\widehat{\boldsymbol{S0}}_n = \boldsymbol{X}_n = \boldsymbol{F}_n \otimes \boldsymbol{I}_{MPFA}$$

$$\boldsymbol{F}_n = \begin{bmatrix} 1/8 & 1/4 & 1/8 \\ 1/8 & 1/4 & 1/8 \\ 0 & 0 & 0 \end{bmatrix}$$

Edge-Aware Guide Image Generation



Edge-aware guide image generation



Four directions

Weight calculation

Example of North direction

Estimated intensity : $\widehat{S0}_{(0,90)}$, $\widehat{S0}_{(45,135)}$

North direction

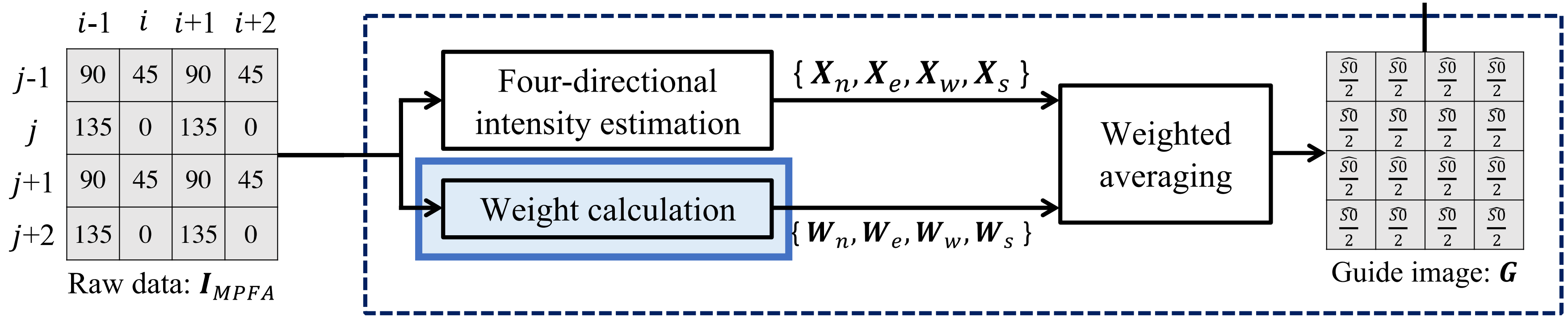
90	**45**	**90**
135	**0**	**135**
90	**45**	**90**

Intensity difference :

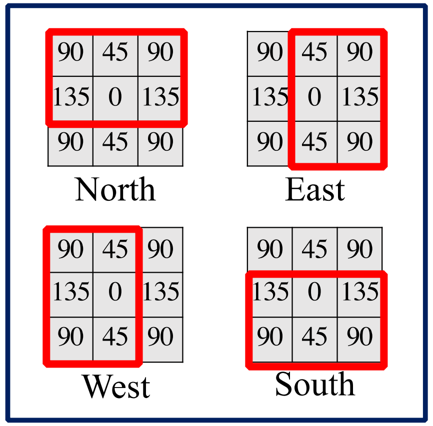
$$\Delta\widehat{S0} = \boldsymbol{\widehat{S0}_{(0,90)}} - \boldsymbol{\widehat{S0}_{(45,135)}}$$

If intensities are constant (meaning no edge) ➡ $\Delta\widehat{S0} = 0$

Edge-Aware Guide Image Generation



Edge-aware guide image generation



Four directions

Weight calculation

Example of North direction

Estimated intensity : $\widehat{S0}_{(0,90)}, \ \widehat{S0}_{(45,135)}$

North direction

90	45	90
135	0	135
90	45	90

Intensity difference :

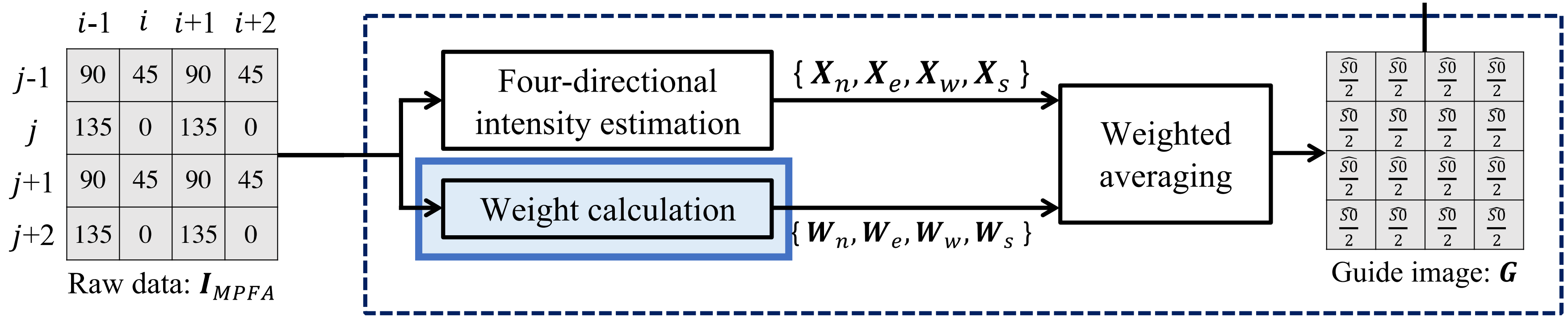
$$\Delta\widehat{S0} = \widehat{S0}_{(0,90)} - \widehat{S0}_{(45,135)}$$

Calculated by filtering

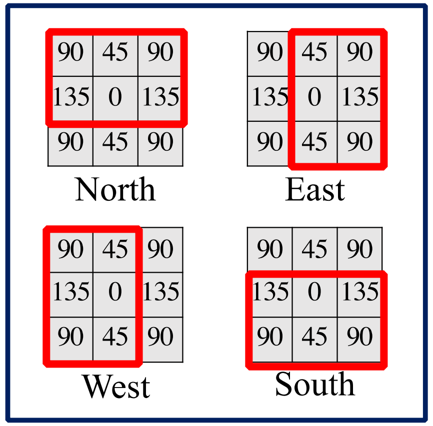
$$\Delta\widehat{S0}_n = H_n \otimes I_{MPFA}$$

$$H_n = \begin{bmatrix} 1/2 & -1 & 1/2 \\ -1/2 & 1 & -1/2 \\ 0 & 0 & 0 \end{bmatrix}$$

Edge-Aware Guide Image Generation



Edge-aware guide image generation



Four directions

Weight calculation

Example of North direction

North direction

90	45	90
135	0	135
90	45	90

Weight:

- Assign a larger weight if intensity difference is small

$$W_n = \frac{1}{S_n \otimes |\Delta\widehat{S0}_n| + \varepsilon},$$

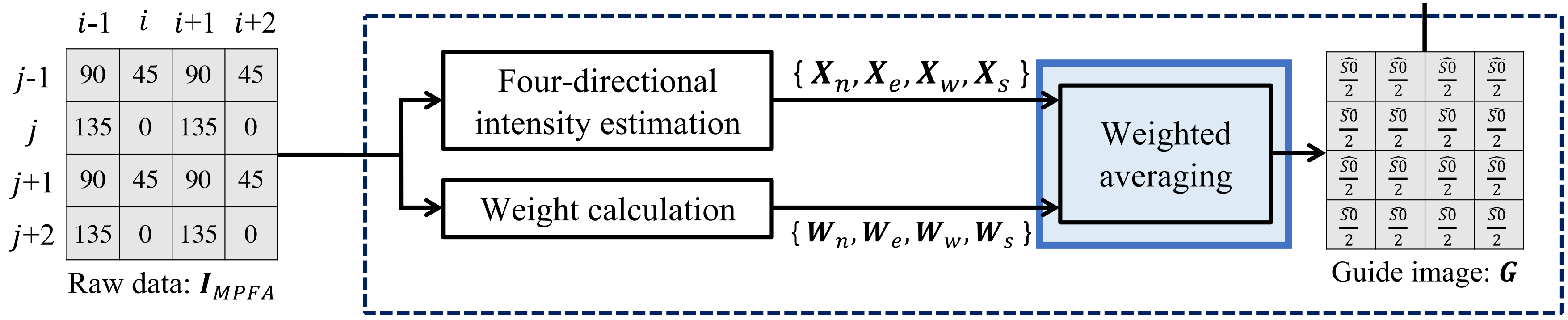
S_n : Smoothing filter

Calculated by filtering

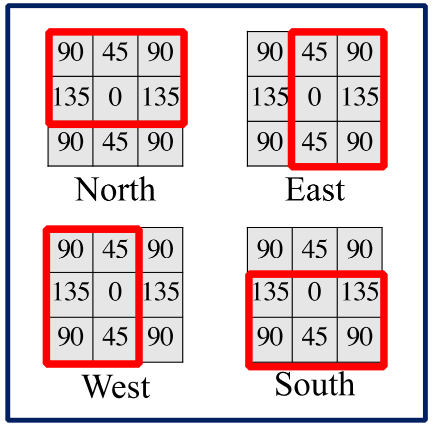
$$\Delta\widehat{S0}_n = H_n \otimes I_{MPFA}$$

$$H_n = \begin{bmatrix} 1/2 & -1 & 1/2 \\ -1/2 & 1 & -1/2 \\ 0 & 0 & 0 \end{bmatrix}$$

Edge-Aware Guide Image Generation



Edge-aware guide image generation



Four directions

Weighted averaging

- Generate the guide image by weighted averaging of four-directional intensities.

Guide image : $G(i,j) = \dfrac{\sum_k W_k(i,j) X_k(i,j)}{\sum_k W_k(i,j)}$,

$k = n, e, w, s$

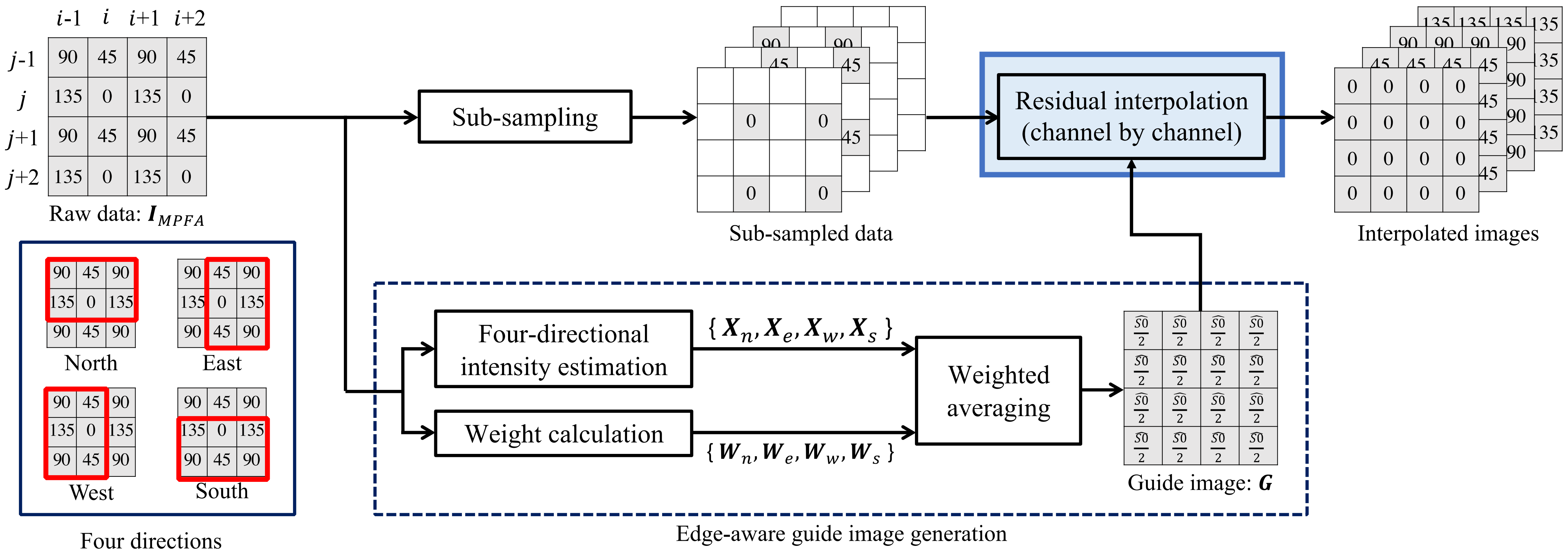
$\boldsymbol{X}_k$: Four-directional Intensity

$\boldsymbol{W}_k$: Weight

Proposed MPFA Demosaicking Method

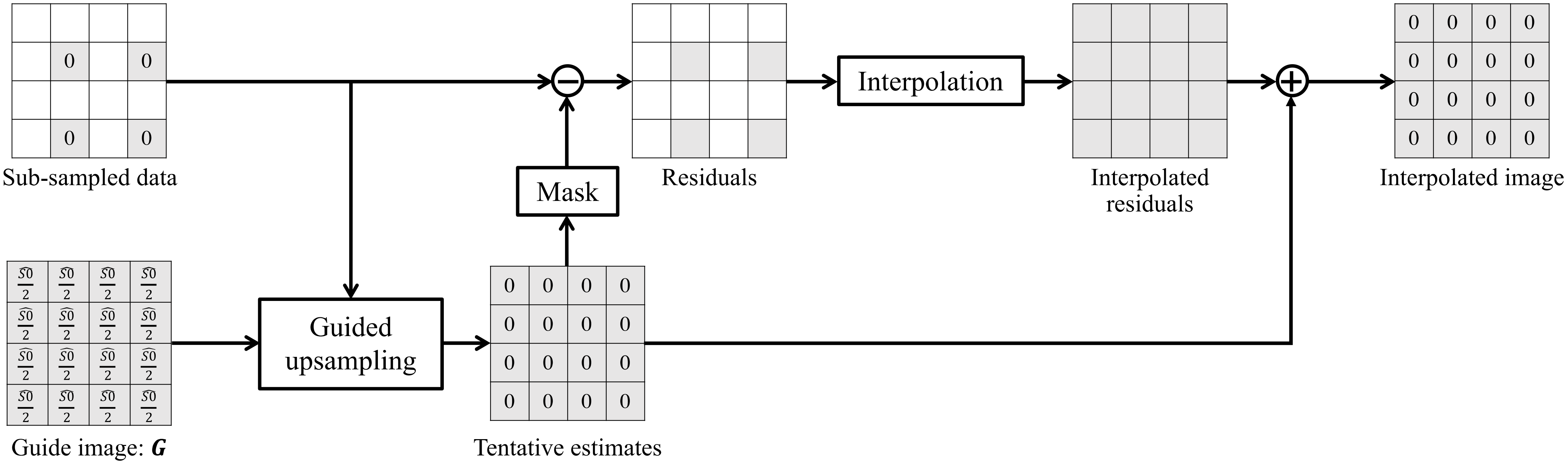
Edge-aware residual interpolation (EARI)

- Interpolate missing values by residual interpolation with the edge-aware guide.



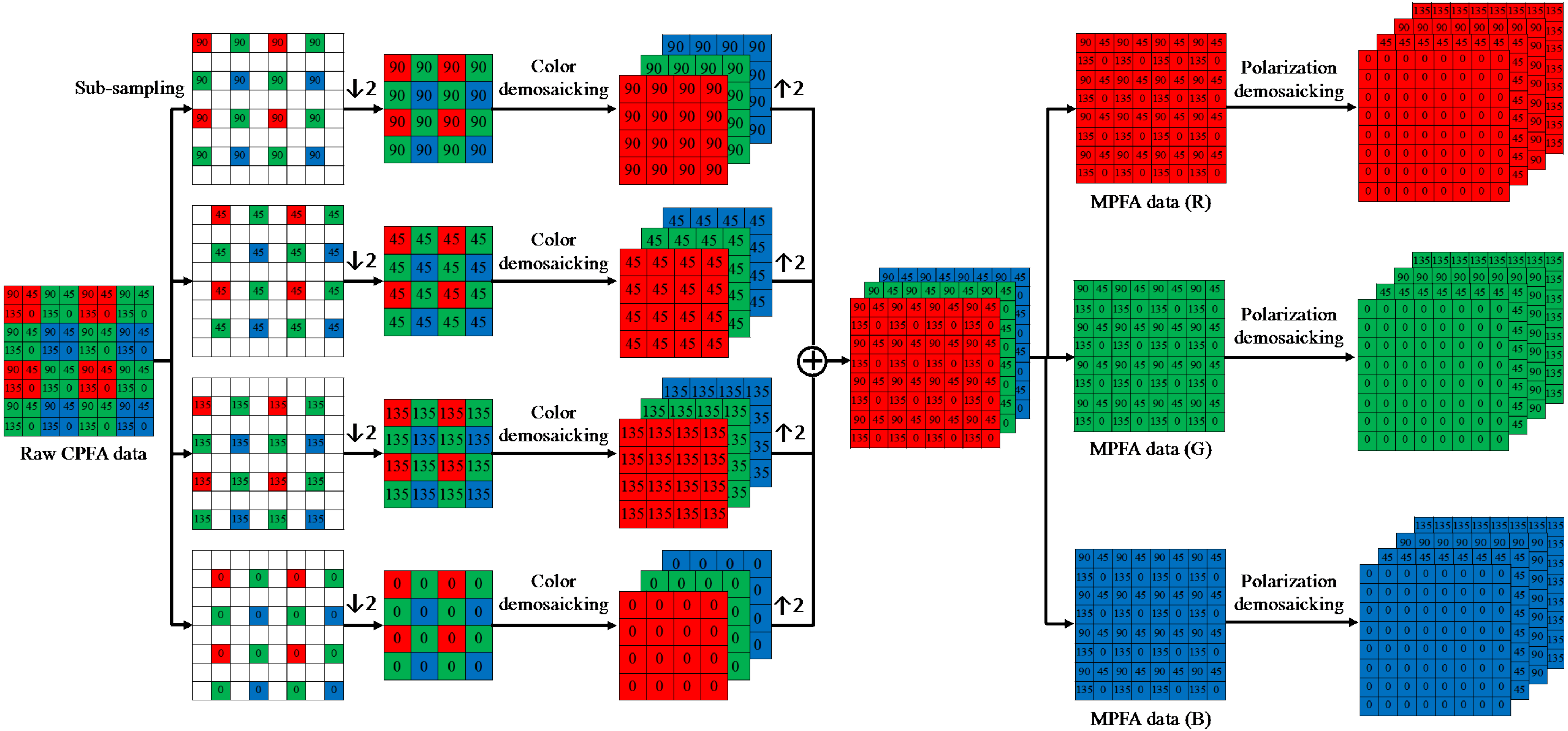
Residual Interpolation

Interpolation method based on a guide image [6]



[6] D. Kiku, Y. Monno, M. Tanaka, and M. Okutomi, “Beyond color difference: Residual interpolation for color image demosaicking,” TIP, 2016.

Extension to CPFA Demosaicking



Color-Polarization Image Dataset

Setups

- JAI CV-M9GE 3-CCD camera
- SIGMAKOKI SPF-50C-32 linear polarizer

- Captured using the rotating linear polarizer placed in front of the 3-CCD camera.

- Captured 1,000 images and averaged them to reduce noise.

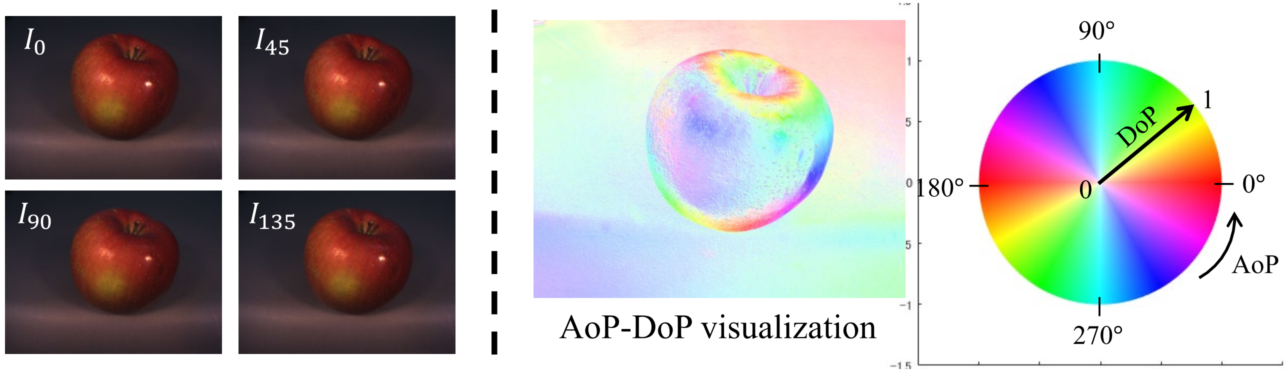
- Captured full 12-channel color-polarization images of 40 scenes.

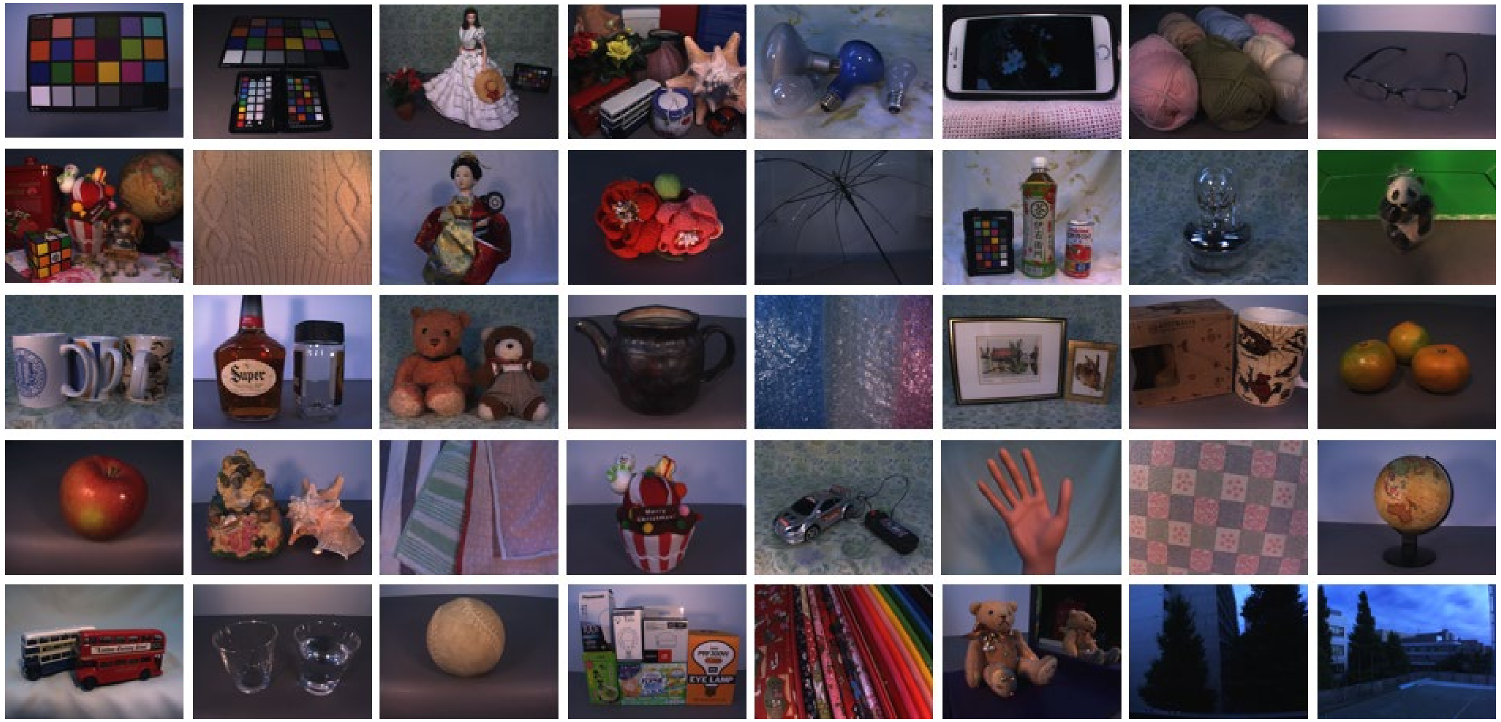
3CCD camera

Rotating polarizer

Setups

Color-Polarization Image Dataset

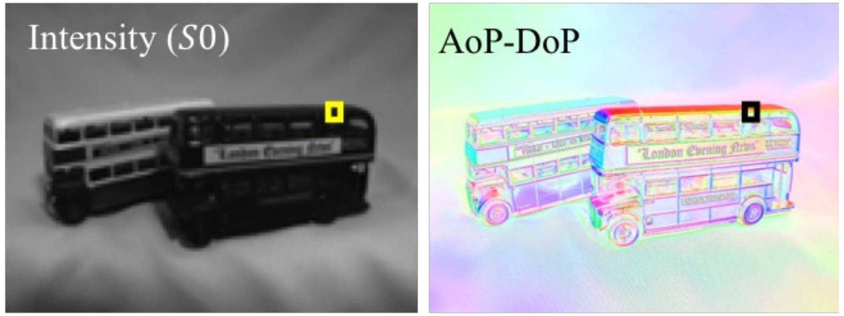




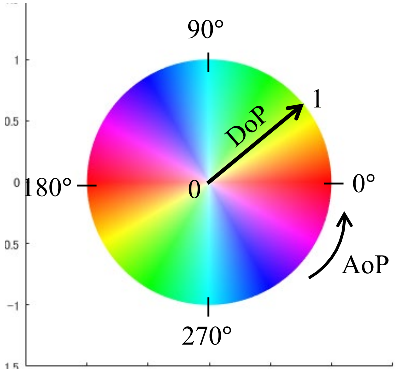
Experimental Results

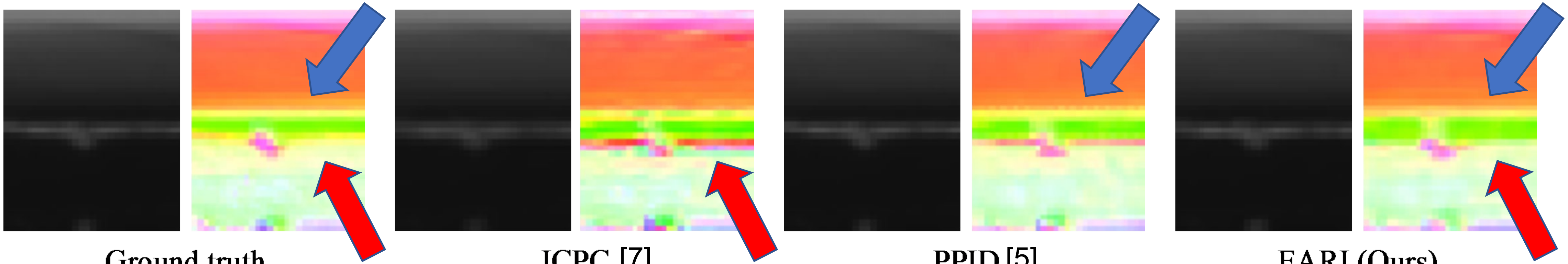
MPFA demosaicking results

Using the green-channel images of our color-polarization dataset



Full ground-truth images





[5] S. Mihoubi et al. "Survey of demosaicking methods for polarization filter array images," Sensors, 2018.
[7] J. Zhang et al. "Image interpolation for division of focal plane polarimeters with intensity correlation," Opt. Exp., 2016.

Experimental Results

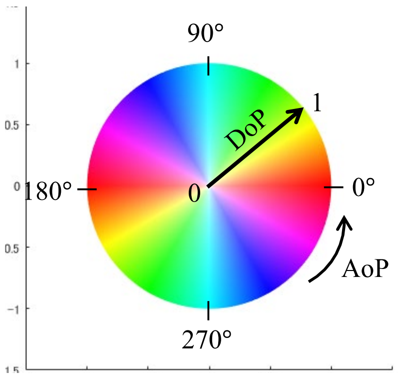
MPFA demosaicking results

PSNR : high **Angle error** : low ➡ Better performance

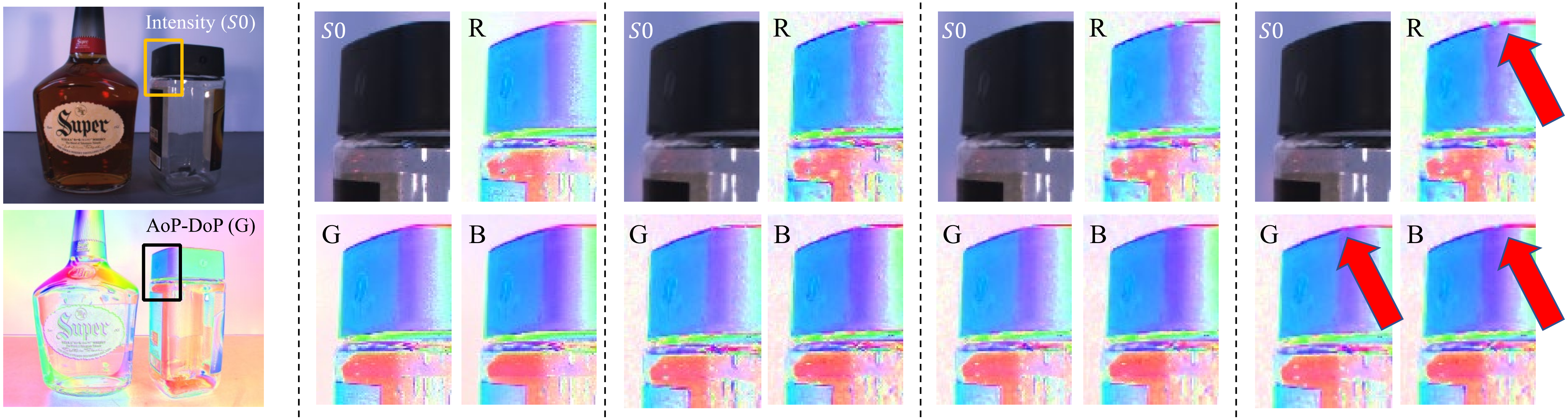
Method	PSNR								Angle error
	I_0	I_{45}	I_{90}	I_{135}	$S0$	$S1$	$S2$	DoP	AoP
Bilinear	42.34	41.58	42.50	41.58	44.89	46.14	45.03	33.70	21.36
Bicubic	43.45	42.48	43.63	42.48	46.22	47.00	45.73	34.46	20.64
ICPC [7]	43.10	42.22	43.23	42.22	45.78	47.01	45.73	34.75	20.50
PPID [5]	46.52	44.52	46.91	44.34	48.94	50.56	47.59	**36.96**	17.65
EARI (Ours)	**47.39**	**44.91**	**47.84**	**44.63**	**49.62**	**51.48**	**47.83**	36.79	**17.13**

[5] S. Mihoubi et al. "Survey of demosaicking methods for polarization filter array images," Sensors, 2018.
[7] J. Zhang et al. "Image interpolation for division of focal plane polarimeters with intensity correlation," Opt. Exp., 2016.

Experimental Results



CPFA demosaicking results



Full ground-truth images
Ground truth
ICPC
PPID
EARI (Ours)

Experimental Results

CPFA demosaicking results

CPSNR : high **Angle error** : low ➡ Better performance

Method (color | polarization)		CPSNR								Angle error
		I_0	I_{45}	I_{90}	I_{135}	$S0$	$S1$	$S2$	DoP	AoP
Bilinear		35.32	34.94	35.47	35.00	36.31	43.29	41.28	31.20	24.98
RI	Bilinear	38.34	37.79	38.50	37.86	40.03	44.09	42.58	31.96	24.15
RI	Bicubic	38.65	38.05	38.81	38.12	40.43	44.30	42.72	32.05	24.11
RI	ICPC [5]	38.61	38.01	38.77	38.09	40.33	44.49	42.87	32.36	23.86
RI	PPID [4]	39.37	38.68	39.57	38.71	40.73	46.34	44.04	**33.98**	22.40
RI	EARI (Ours)	**39.41**	**38.72**	**39.62**	**38.72**	**40.76**	**46.49**	**44.10**	33.74	**22.18**

Conclusion

Dataset and code are available!

- Proposed an MPFA demosaicking method based on edge-aware residual interpolation (EARI) and extend it to CPFA demosaicking.
- Constructed full color-polarization image dataset captured using a 3-CCD camera and a rotating polarizer.
- Demonstrated that our EARI-based method outperforms existing methods.
- The dataset and the source code of our proposed method are available.

http://www.ok.sc.e.titech.ac.jp/res/PolarDem/index.html