# Spectral Reflectance Estimation Using Projector with Unknown Spectral Power Distribution

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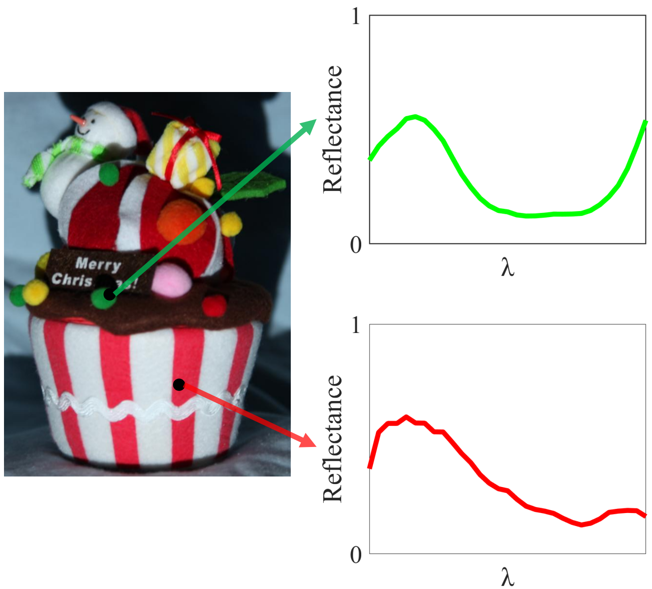
# Introduction

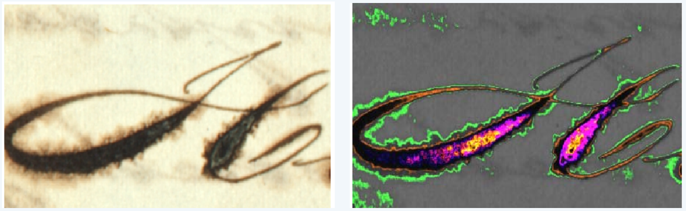
## Spectral Reflectance




Reflectance in wavelength domain

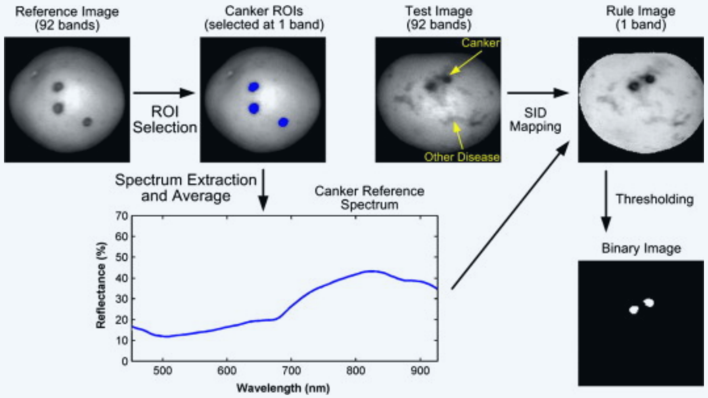
## Application

- Historical works analysis



[1]

- Food inspection




[2]


[1]. H. Liang, “Advances in multispectral and hyperspectral imaging for archaeology and art conservation,” Applied Physics A, vol. 106, no. 2, pp. 309–323, 2012.

[2]. J. Qin, K. Chao, M. S. Kim, R. Lu, and T. F. Burks, “Hyperspectral and multispectral imaging for evaluating food safety and quality,” Journal of Food Engineering, vol. 118, no. 2, pp. 157–171, 2013.

# Related Works (Active Lighting Method)

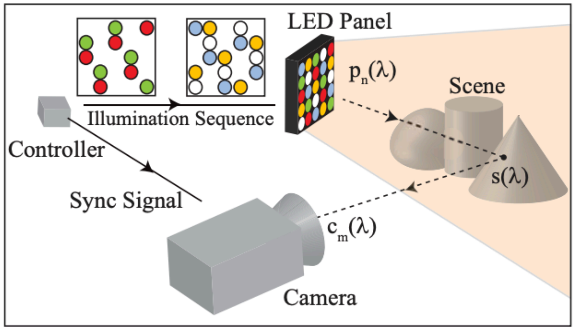
## Lighting System

Light source with variable spectrum

+

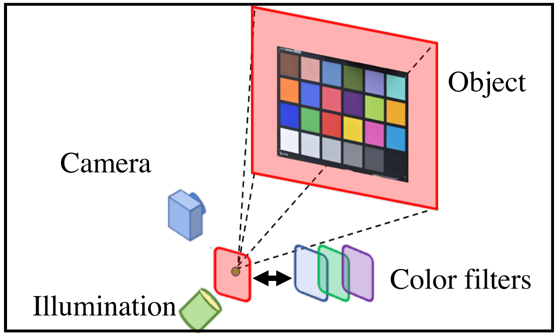
Consumer RGB camera

- LED cluster system




[5]

- Illumination and color filter




[6]


[5]. J. Park, M. Lee, M. D. Grossberg, and S. K. Nayar, "Multispectral imaging using multiplexed illumination," Proc. of IEEE Int. Conf. on Computer Vision (ICCV), pp. 1–8, 2007.

[6]. C. Cui, H. Yoo, and M. Ben-Ezra, "Multi-spectral imaging by optimized wide band illumination," Int. Journal of Computer Vision, vol. 86, pp. 140–151, 2010.

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## Lighting System

Light source with variable spectrum

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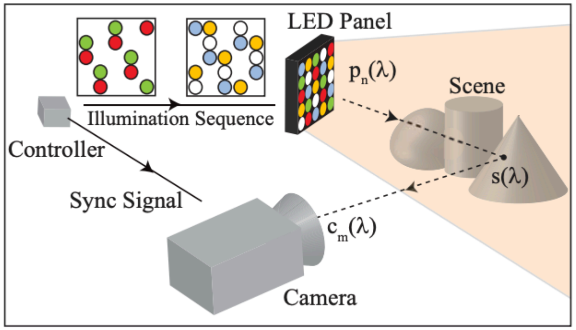
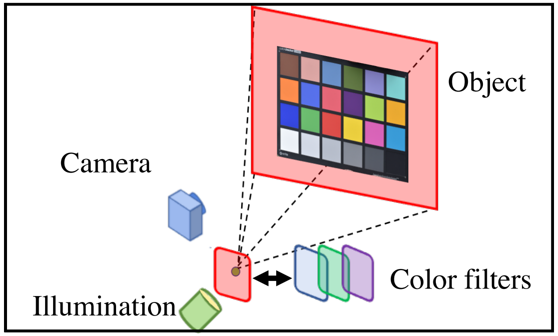


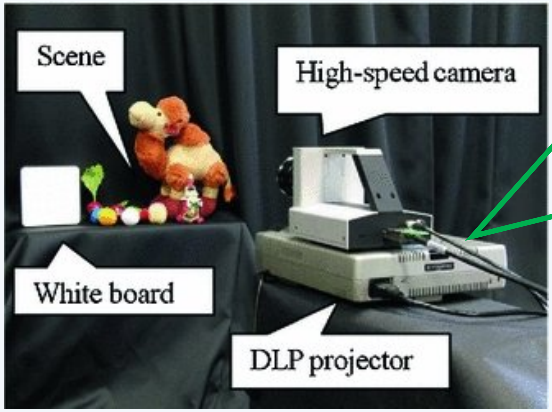

[5]

- Illumination and color filter

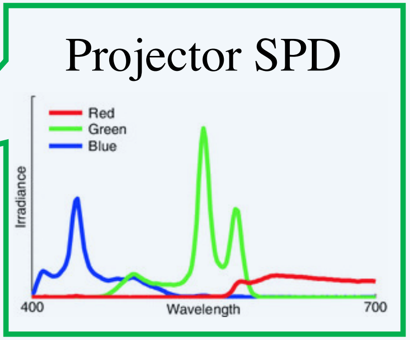



[6]

## Projector-Camera System




[7]




○ Projector-Camera setup has better trade-off regarding accuracy and cost

○ This setup can be used to acquire the 3D model of an object. [8]

△ Spectral power distribution(SPD) is assumed to be known.

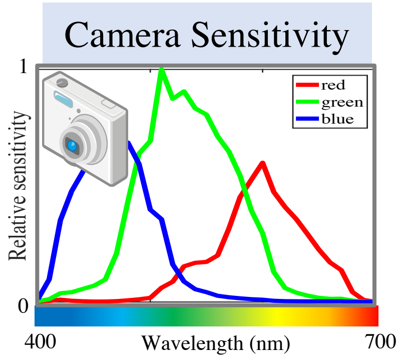

[7]. S. Han, I. Sato, T. Okabe, and Y. Sato, "Fast spectral reflectance recovery using DLP projector," Int. Journal of Computer Vision, vol. 110, no. 2, pp. 172–184, 2014.

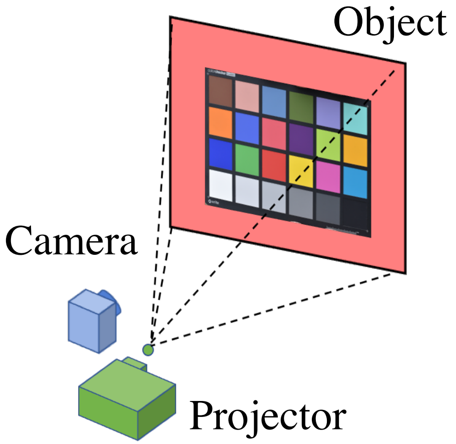
[8]. C. Li, Y. Monno, H. Hidaka, and M. Okutomi, "Pro-Cam SSfM: Projector-camera system for structure and spectral reflectance from motion," Proc. of IEEE Int. Conf. on Computer Vision (ICCV)

# Our Target

## Image Acquisition

known

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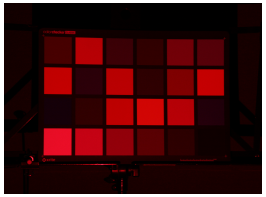
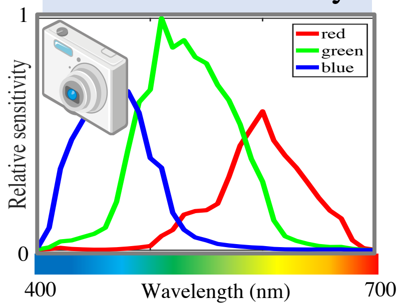


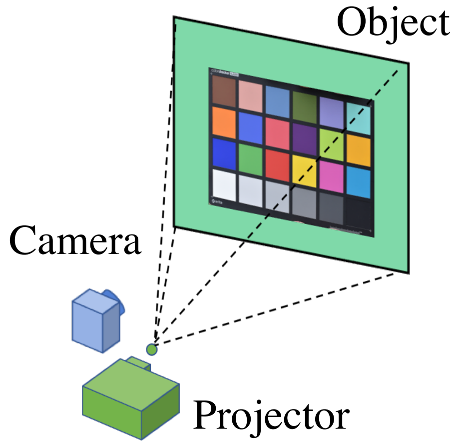
# Our Target

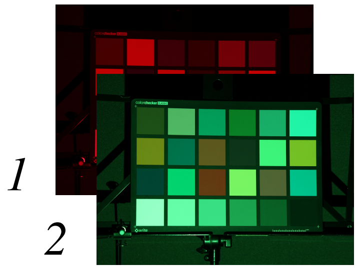
## Image Acquisition

known

Camera Sensitivity



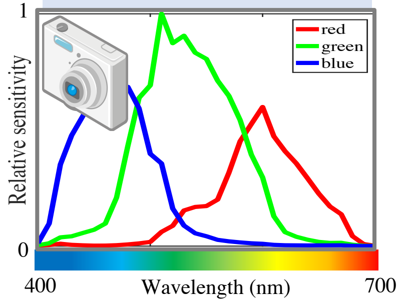



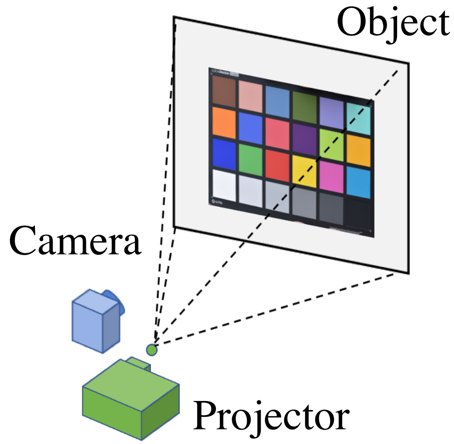
# Our Target

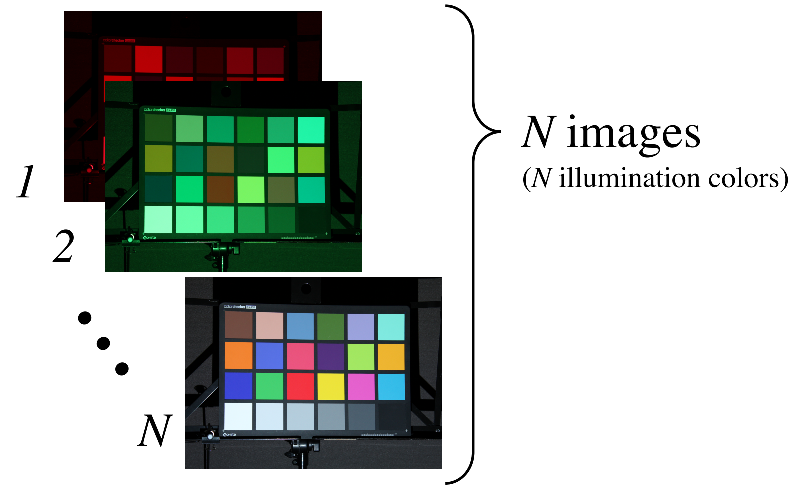
## Image Acquisition

known

Camera Sensitivity



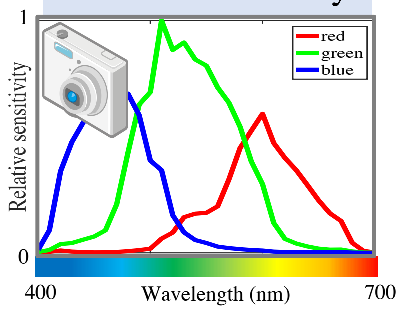



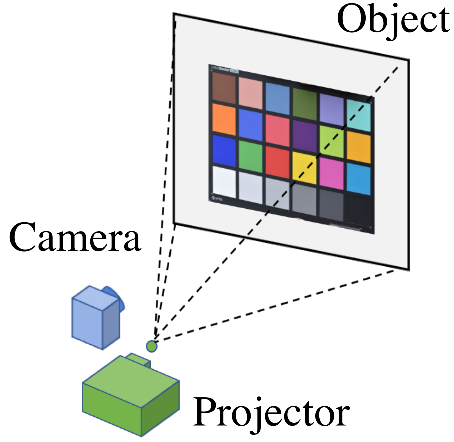
# Our Target

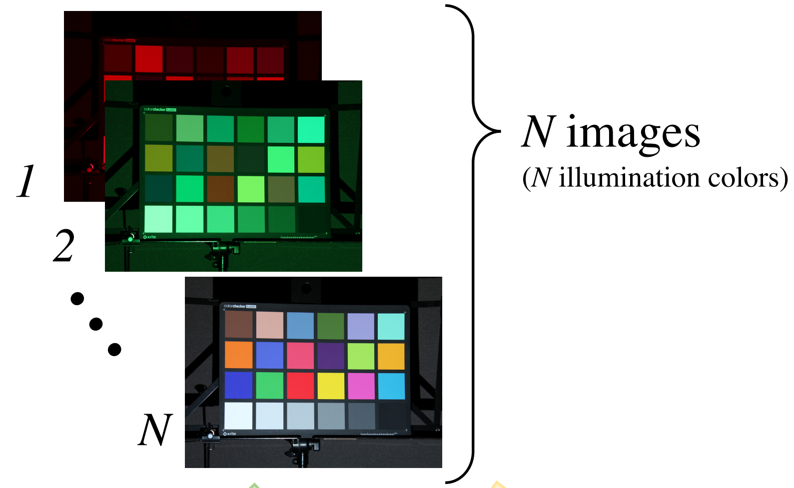
## Image Acquisition

known

Camera Sensitivity

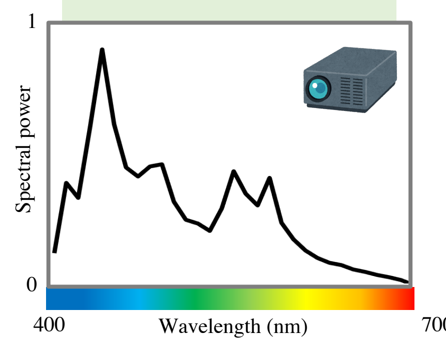


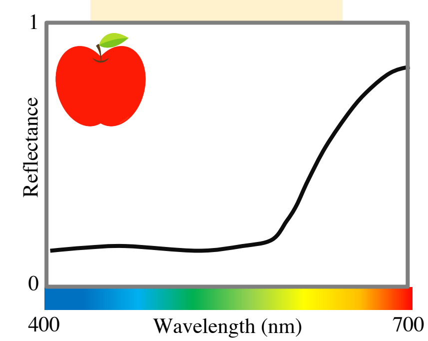




Estimation

SPD (nth color )




Reflectance



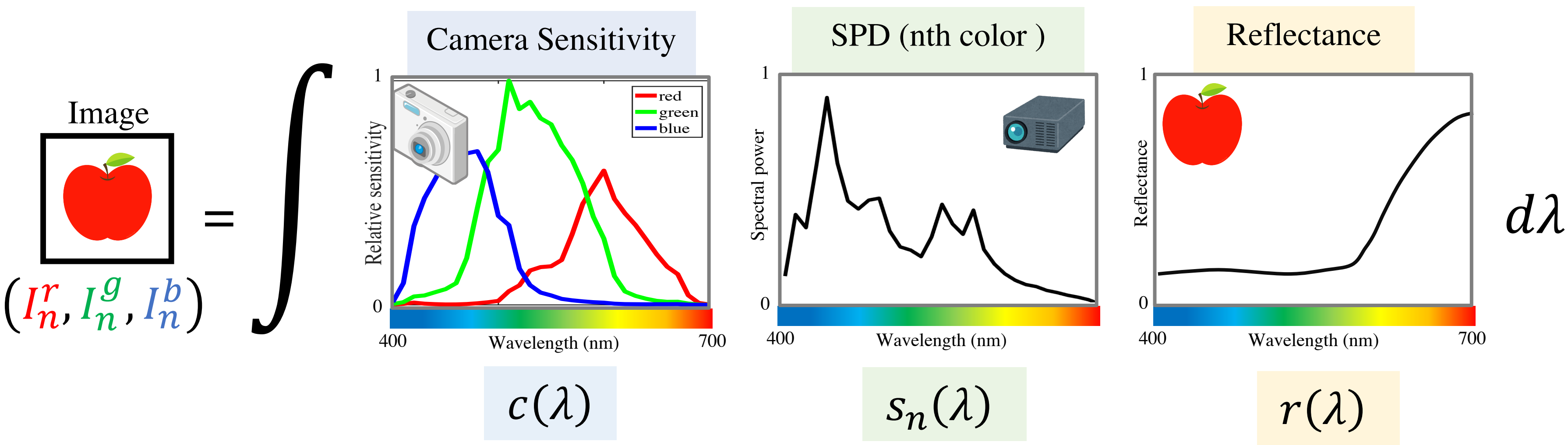

## Our Work

- Joint estimation of spectral reflectance and spectral power distribution(SPD)
- Make projector illumination basis for SPD estimation.

# Image Formulation Model

**Imaging Model**

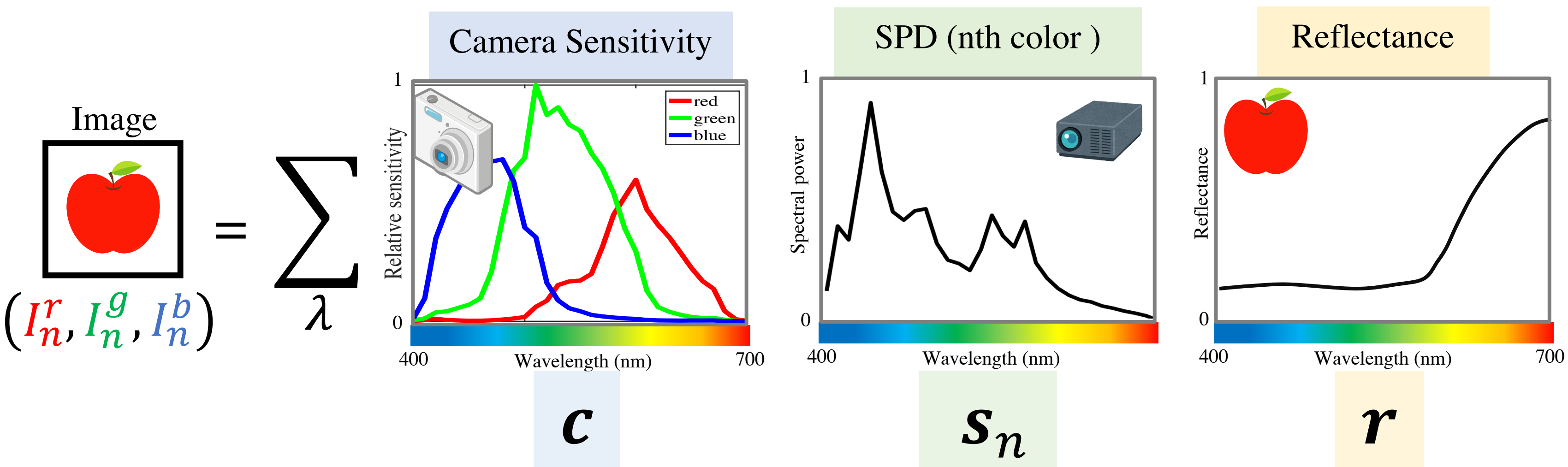
$$I_n = \int_{\Omega} c(\lambda)\, s_n(\lambda)\, r(\lambda) d\lambda \quad (\Omega = [400\text{nm}, 700\text{nm}])$$



# Image Formulation Model

**Imaging Model**

$$I_n = \boldsymbol{c}^T \; diag(\, \boldsymbol{s}_n \,) \; \boldsymbol{r} \qquad ([400\text{nm}, 700\text{nm}] \text{ in } 10\text{nm})$$

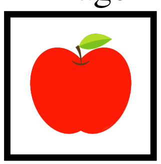


# Spectral Reflectance Model

## Imaging Model

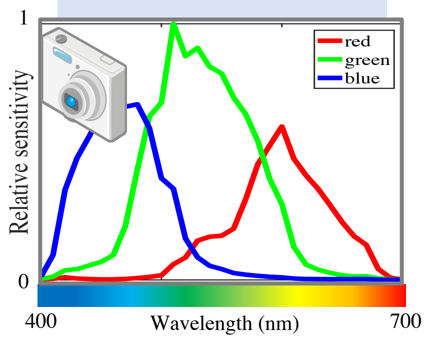
$$I_n = \boldsymbol{c}^T \; diag(\boldsymbol{s}_n) \; \boldsymbol{r} \qquad ([400\text{nm}, 700\text{nm}] \text{ in } 10\text{nm})$$

Image

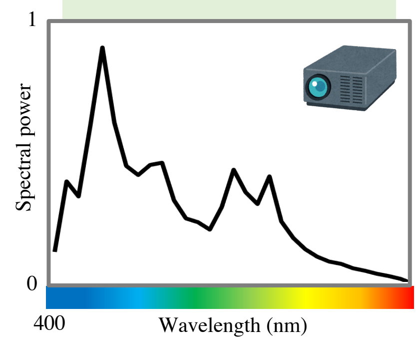


$$(I_n^r, I_n^g, I_n^b) = \sum_\lambda$$

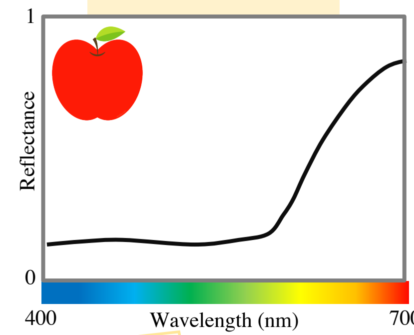
Camera Sensitivity




SPD (nth color )



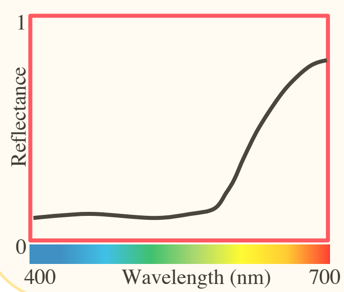

Reflectance




**Spectral reflectance** $r(\lambda)$

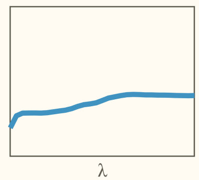
$$r(\lambda) = \sum_k^{N_r(=6)} \alpha_i b_i^{ref}(\lambda) = \mathbf{B}^{ref} \boxed{\boldsymbol{\alpha}}$$

$\mathbf{B}^{ref}$: Ref Basis Matrix $(N_\lambda \times N_r)$



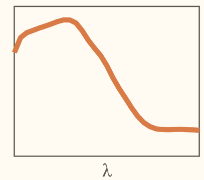

$= \alpha_1$

$b_1^{ref}(\lambda)$



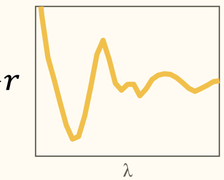

$+ \alpha_2$

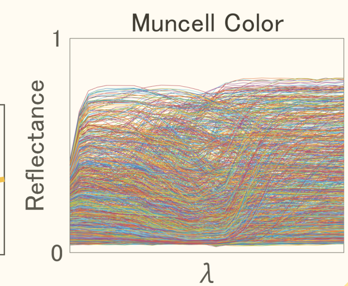
$b_2^{ref}(\lambda)$




$\cdots + \alpha_{N^r}$

$b_{N^r}^{ref}(\lambda)$



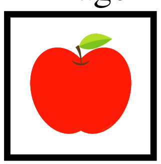



# Projector SPD Model

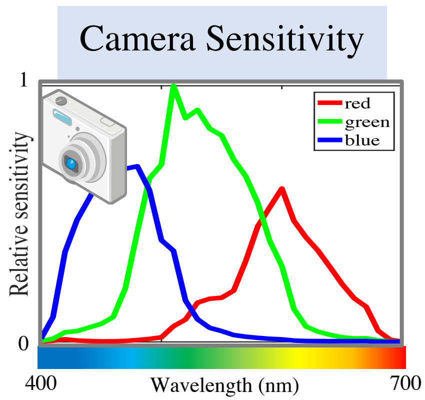
## Imaging Model

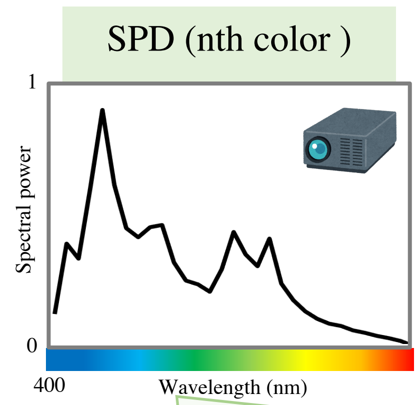
$$I_n = \boldsymbol{c}^T \; diag(\boldsymbol{s}_n) \; \boldsymbol{r} \qquad \text{([400nm, 700nm] in 10nm)}$$

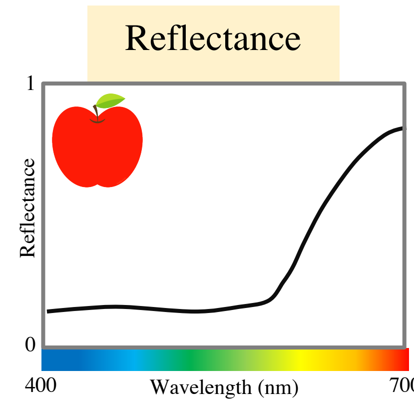
Image



$(I_n^r, I_n^g, I_n^b) = \sum_{\lambda}$



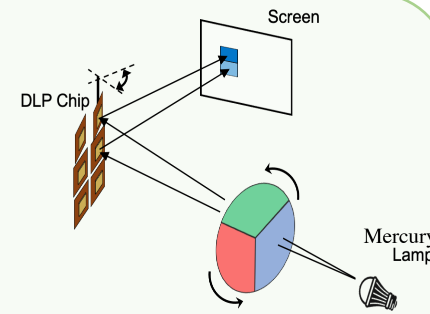




**Spectral power distribution(SPD)** $s_n(\lambda)$

$$\boxed{\boldsymbol{s}_n(\lambda) = \gamma_{r,n}\boldsymbol{s}_r(\lambda) + \gamma_{g,n}\boldsymbol{s}_g(\lambda) + \gamma_{b,n}\boldsymbol{s}_b(\lambda)}$$

Primary RGB color is described in low dimensional model

$$\boldsymbol{s}_r = \mathbf{B}_r^{ill}\boxed{\boldsymbol{\beta}_r}, \quad \boldsymbol{s}_g = \mathbf{B}_g^{ill}\boxed{\boldsymbol{\beta}_g}, \quad \boldsymbol{s}_b = \mathbf{B}_b^{ill}\boxed{\boldsymbol{\beta}_b}$$



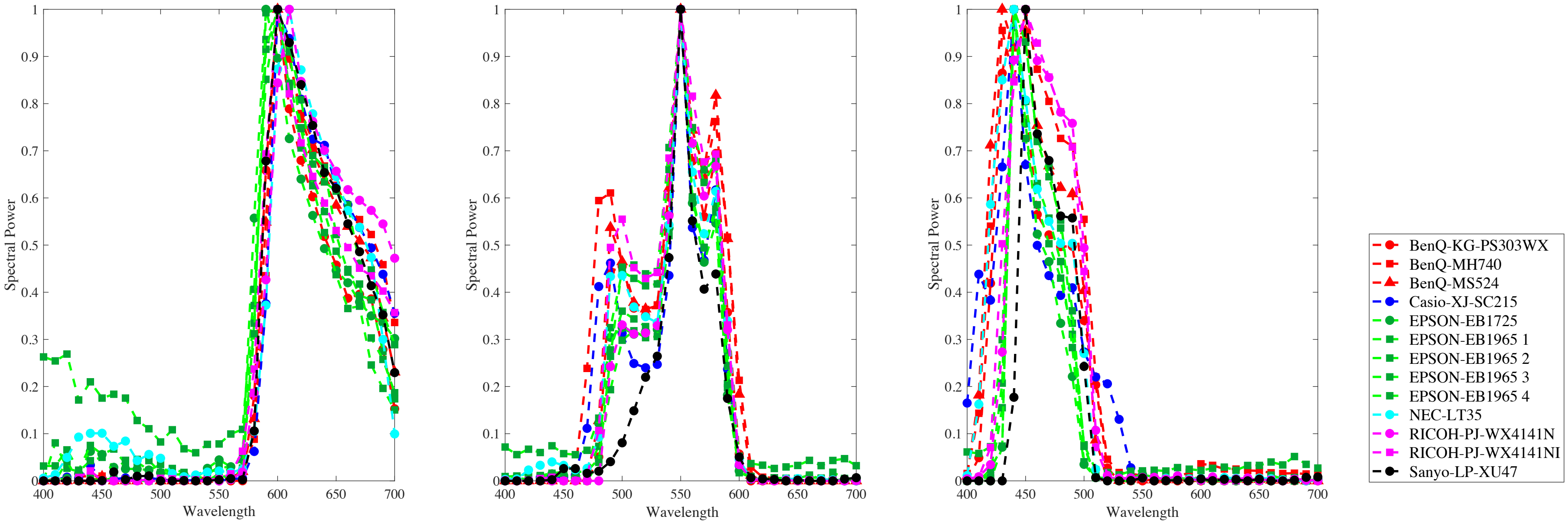

$\mathbf{B}_r^{ill}, \mathbf{B}_g^{ill}, \mathbf{B}_b^{ill}$: Ill Basis Matrix $(N_\lambda \times N_s)$

# Projector SPD Dataset

Collect RGB projector spectral dataset for RGB primary basis function.

- This dataset is made from only mercury lamp projector

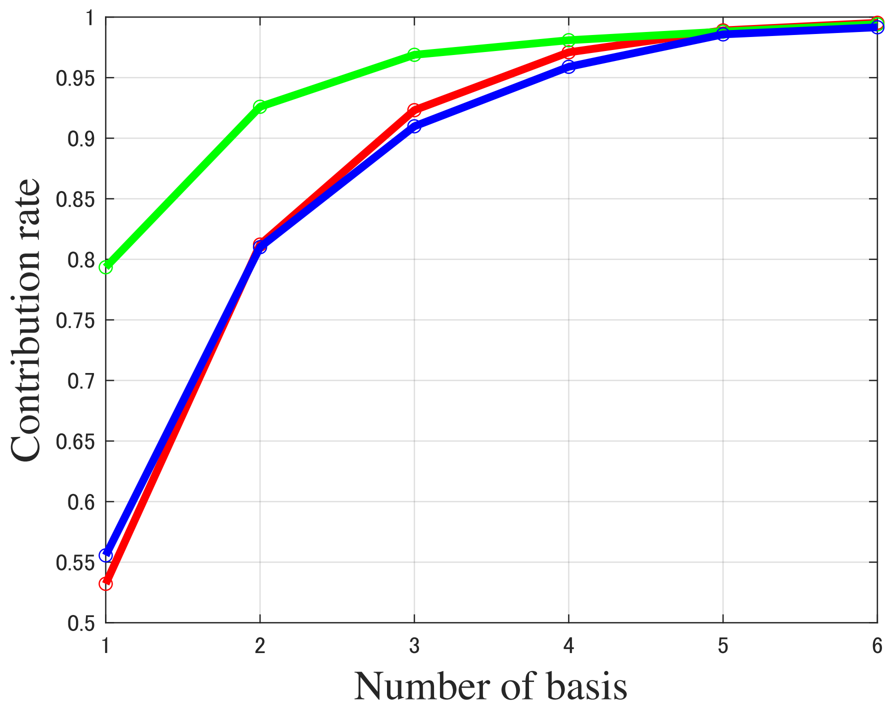
Red : $\boldsymbol{s}_r(\lambda)$ Green : $\boldsymbol{s}_g(\lambda)$ Blue : $\boldsymbol{s}_b(\lambda)$



# Projector SPD Basis

RGB spectra basis are made from projector spectral dataset

- From contribution rate, we choose the number of basis of each primary color is 6



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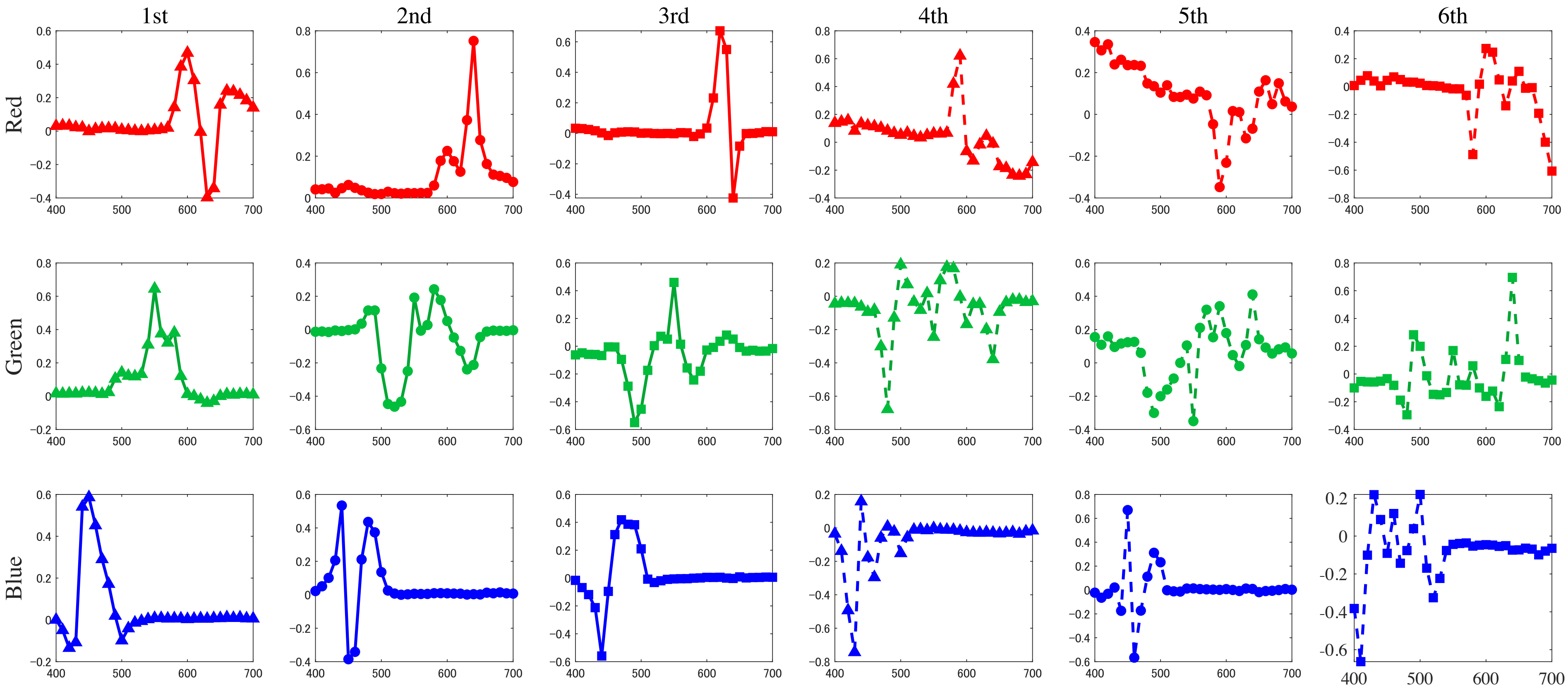


# Spectral Reconstruction

**Cost Function**

Color rendering term

$$E(\boldsymbol{\alpha}\ ,\boldsymbol{\beta}) = \frac{1}{NP}\sum_{m}\sum_{n}\sum_{p}(I_{m,n,p} - \underbrace{\boldsymbol{c}_m^T\, diag(\boldsymbol{s}_n)\, \boldsymbol{r}_p}_{\hat{I}_{m,n,p}\text{ (Imaging model)}})^2$$

Channel

Illumination

Pixel

$$+\frac{\sigma_1}{N}\sum_{n}\left\|\frac{\delta^2 \boldsymbol{s_n}}{\delta^2\lambda}\right\|_2^2 + \frac{\sigma_2}{P}\sum_{p}\left\|\frac{\delta^2 \boldsymbol{r_n}}{\delta^2\lambda}\right\|_2^2$$

Spectral smoothness term

$\boldsymbol{s}_n$ : SPD of n-th illumination color

$\boldsymbol{r}_p$ : Spectral reflectance of p-th pixel

$\boldsymbol{c}_m$ : Camera sensitivity of m-th channel

$N$ : The number of illumination colors

$P$ : The number of pixels

# Spectral Reconstruction

**Cost Function**

Color rendering term

$$E(\boldsymbol{\alpha}, \boldsymbol{\beta}) = \frac{1}{NP} \sum_{m} \sum_{n} \sum_{p} (I_{m,n,p} - \underbrace{\boxed{\boldsymbol{\alpha}_p^T} \mathbf{B}^{ref^T} diag(\boldsymbol{c}_m^T) \mathbf{B}^{ill} \boldsymbol{\Gamma}(\boldsymbol{\gamma}_n) \boxed{\boldsymbol{\beta}}}_{\mathbf{W}_{m,n}})^2$$

Channel

Illumination

Pixel

$$+ \frac{\sigma_1}{N} \sum_{n} \left\| \frac{\delta^2 \mathbf{B}^{ill}}{\delta^2 \lambda} \boldsymbol{\Gamma}(\boldsymbol{\gamma}_n) \boxed{\boldsymbol{\beta}} \right\|_2^2 + \frac{\sigma_2}{P} \sum_{p} \left\| \frac{\delta^2 \mathbf{B}^{ref}}{\delta^2 \lambda} \boxed{\boldsymbol{\alpha}_p} \right\|_2^2$$

Spectral smoothness term

$\mathbf{B}^{ill} \boldsymbol{\Gamma}(\boldsymbol{\gamma}_n) \boxed{\boldsymbol{\beta}} \leftarrow \boldsymbol{s}_n$ : SPD of n-th illumination color

$\mathbf{B}^{ref} \boxed{\boldsymbol{\alpha}_p} \leftarrow \boldsymbol{r}_p$ : Spectral reflectance of p-th pixel

$\boldsymbol{c}_m$ : Camera sensitivity of m-th channel

$N$ : The number of illumination colors

$P$ : The number of pixels

$\boldsymbol{\Gamma}(\boldsymbol{\gamma}_n)$ : Matrix encoding the gains for primary of n-th color

# Spectral Reconstruction

## Cost Function

color rendering term

$$E(\boldsymbol{\alpha}, \boldsymbol{\beta}) = \frac{1}{NP}\sum_{m}\sum_{n}\sum_{p}(I_{m,n,p} - \boxed{\boldsymbol{\alpha}_p^T}\ \mathbf{W}_{m,n}\ \boxed{\boldsymbol{\beta}})^2$$

Channel

Illumination

Pixel

Spectral smoothness term

$$+\frac{\sigma_1}{N}\sum_{n}\left\|\frac{\delta^2\ \mathbf{B}^{ill}}{\delta^2\lambda}\boldsymbol{\Gamma}(\boldsymbol{\gamma}_n)\boxed{\boldsymbol{\beta}}\right\|_2^2 + \frac{\sigma_2}{P}\sum_{p}\left\|\frac{\delta^2\mathbf{B}^{ref}}{\delta^2\lambda}\boxed{\boldsymbol{\alpha}_p}\right\|_2^2$$

## Constrains

- non-zero constrain of illumination

$$\boldsymbol{B}_{\boldsymbol{r}}^{ill}\ \beta_{\boldsymbol{r}} \geq \mathbf{0}\ ,\ \boldsymbol{B}_{\boldsymbol{g}}^{ill}\ \beta_{\boldsymbol{g}} \geq \mathbf{0}\ ,\ \boldsymbol{B}_{\boldsymbol{b}}^{ill}\ \beta_{\boldsymbol{b}} \geq \mathbf{0}$$

- non-zero constrain of reflectance

$$\boldsymbol{B}^{ref}\alpha_k \geq \mathbf{0}$$

- Remove the ambiguity of reflectance and illumination

$$\mathbf{B}^{ill}\ \boldsymbol{\Gamma}(\boldsymbol{\gamma}_n)\ \boldsymbol{\beta})(\lambda_{\boldsymbol{f}}) = 1$$

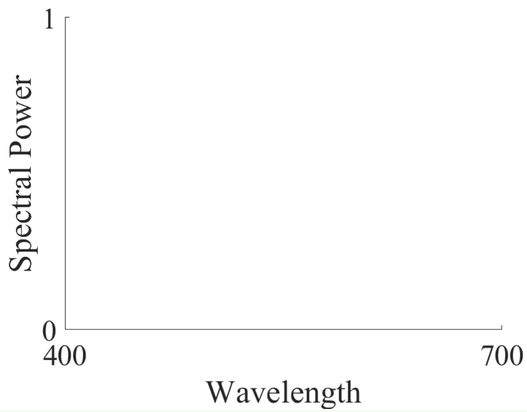
# Alternate Spectral Estimation

**Cost Function**

$$E(\boldsymbol{\alpha},\boldsymbol{\beta}) = \underbrace{\frac{1}{NP}\sum_{m}\sum_{n}\sum_{p}\left(I_{m,n,p} - \boxed{\boldsymbol{\alpha}_p^T}\,\mathbf{W}_{m,n}\,\boxed{\boldsymbol{\beta}}\right)^2}_{\text{color rendering term}} \underbrace{+ \frac{\sigma_1}{N}\sum_{n}\left\|\frac{\delta^2\,\mathbf{B}^{ill}}{\delta^2\lambda}\boldsymbol{\Gamma}(\boldsymbol{\gamma}_n)\boxed{\boldsymbol{\beta}}\right\|_2^2 + \frac{\sigma_2}{P}\sum_{p}\left\|\frac{\delta^2\,\mathbf{B}^{ref}}{\delta^2\lambda}\boxed{\boldsymbol{\alpha}_p}\right\|_2^2}_{\text{Spectral smoothness term}}$$

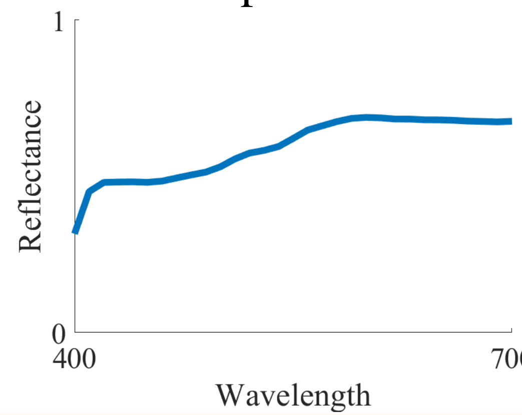
Channel ($m$)
Illumination ($n$)
Pixel ($p$)

**Solution** $\boldsymbol{\alpha}_p$ (Reflectance) and $\boldsymbol{\beta}$ (illumination SPDs) are alternately derived




SPD (projector primary RGB)

1st Spectral reflectance basis




Spectral reflectance (point ***p***)

# Alternate Spectral Estimation

**Cost Function**

$$E(\boldsymbol{\alpha},\boldsymbol{\beta}) = \frac{1}{NP}\sum_{m}\sum_{n}\sum_{p}(I_{m,n,p} - \boxed{\boldsymbol{\alpha}_p^T}\,\mathbf{W}_{m,n}\boxed{\boldsymbol{\beta}})^2$$

color rendering term

Channel

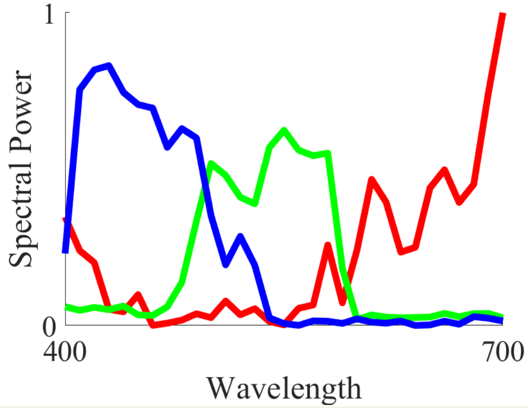
Illumination

Pixel

Spectral smoothness term

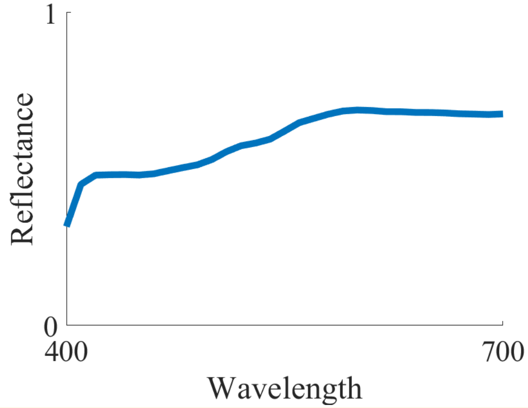
$$+\frac{\sigma_1}{N}\sum_{n}\left\|\frac{\delta^2\,\mathbf{B}^{ill}}{\delta^2\lambda}\boldsymbol{\Gamma}(\boldsymbol{\gamma}_n)\boxed{\boldsymbol{\beta}}\right\|_2^2 + \frac{\sigma_2}{P}\sum_{p}\left\|\frac{\delta^2\mathbf{B}^{ref}}{\delta^2\lambda}\boxed{\boldsymbol{\alpha}_p}\right\|_2^2$$

**Solution** $\boldsymbol{\alpha}_p$ (Reflectance) and $\boldsymbol{\beta}$ (illumination SPDs) are alternately derived




SPD (projector primary RGB)

1st Spectral reflectance basis




Spectral reflectance (point $\boldsymbol{p}$)

# Alternate Spectral Estimation

**Cost Function**

color rendering term

$$E(\boldsymbol{\alpha}\ ,\boldsymbol{\beta}) = \frac{1}{NP}\sum_{m}\sum_{n}\sum_{p}\left(I_{m,n,p} - \boxed{\boldsymbol{\alpha}_p^T}\ \mathbf{W}_{m,n}\ \boxed{\boldsymbol{\beta}}\right)^2$$

Spectral smoothness term

$$+\frac{\sigma_1}{N}\sum_{n}\left\|\frac{\delta^2\ \mathbf{B}^{ill}}{\delta^2\lambda}\boldsymbol{\Gamma}(\boldsymbol{\gamma}_n)\boxed{\boldsymbol{\beta}}\right\|_2^2 + \frac{\sigma_2}{P}\sum_{p}\left\|\frac{\delta^2\mathbf{B}^{ref}}{\delta^2\lambda}\boxed{\boldsymbol{\alpha}_p}\right\|_2^2$$

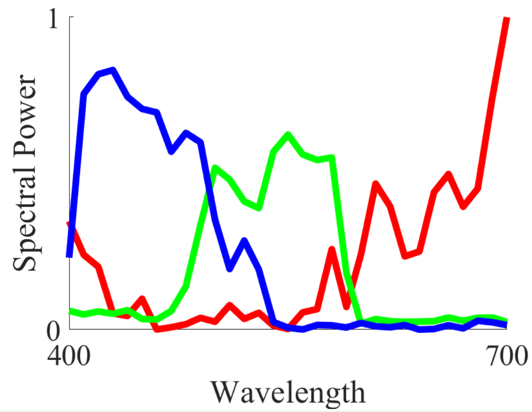
Channel

Illumination

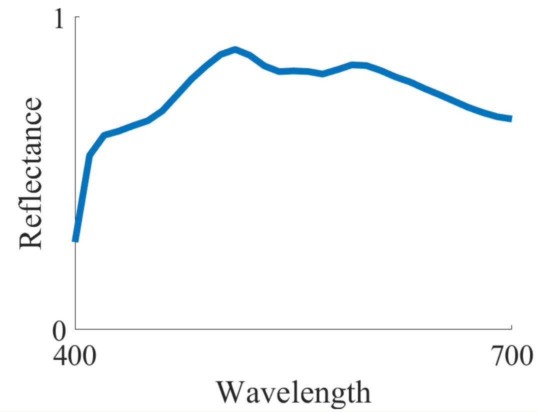
Pixel

**Solution**

$\boldsymbol{\alpha}_p$ (Reflectance) and $\boldsymbol{\beta}$ (illumination SPDs) are alternately derived




SPD (projector primary RGB)




Spectral reflectance (point $\boldsymbol{p}$)

# Alternate Spectral Estimation

**Cost Function**

color rendering term

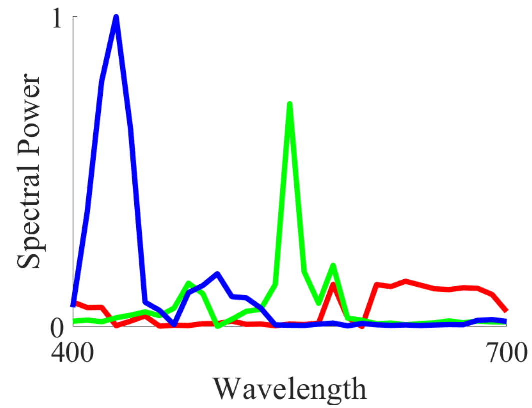
$$E(\boldsymbol{\alpha}, \boldsymbol{\beta}) = \frac{1}{NP}\sum_{m}\sum_{n}\sum_{p}\left(I_{m,n,p} - \boxed{\boldsymbol{\alpha}_p^T}\ \mathbf{W}_{m,n}\ \boxed{\boldsymbol{\beta}}\right)^2$$

Channel
Illumination
Pixel

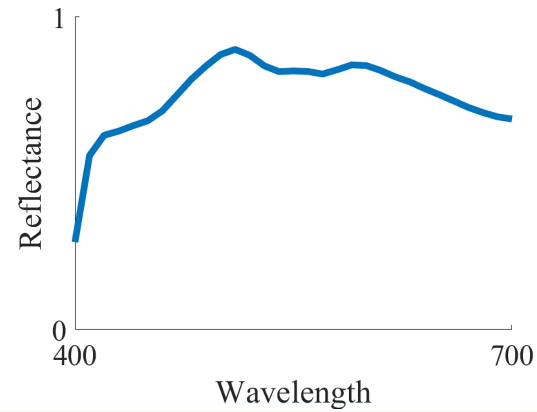
Spectral smoothness term

$$+\frac{\sigma_1}{N}\sum_{n}\left\|\frac{\delta^2\ \mathbf{B}^{ill}}{\delta^2\lambda}\boldsymbol{\Gamma}(\boldsymbol{\gamma}_n)\boxed{\boldsymbol{\beta}}\right\|_2^2 + \frac{\sigma_2}{P}\sum_{p}\left\|\frac{\delta^2\mathbf{B}^{ref}}{\delta^2\lambda}\boxed{\boldsymbol{\alpha}_p}\right\|_2^2$$

**Solution** $\boldsymbol{\alpha}_p$ (Reflectance) and $\boldsymbol{\beta}$ (illumination SPDs) are alternately derived




SPD (projector primary RGB)




Spectral reflectance (point $\boldsymbol{p}$)

# Alternate Spectral Estimation

## Cost Function

color rendering term

$$E(\boldsymbol{\alpha}, \boldsymbol{\beta}) = \frac{1}{NP}\sum_{m}\sum_{n}\sum_{p}\left(I_{m,n,p} - \boxed{\boldsymbol{\alpha}_p^T}\,\mathbf{W}_{m,n}\,\boxed{\boldsymbol{\beta}}\right)^2$$

Channel

Illumination

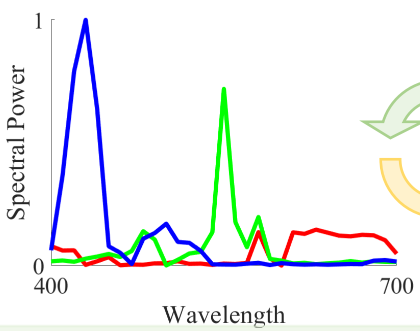
Pixel

Spectral smoothness term

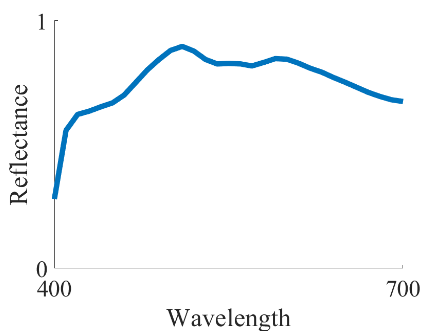
$$+\frac{\sigma_1}{N}\sum_{n}\left\|\frac{\delta^2\,\mathbf{B}^{ill}}{\delta^2\lambda}\boldsymbol{\Gamma}(\boldsymbol{\gamma}_n)\boxed{\boldsymbol{\beta}}\right\|_2^2 + \frac{\sigma_2}{P}\sum_{p}\left\|\frac{\delta^2\,\mathbf{B}^{ref}}{\delta^2\lambda}\boxed{\boldsymbol{\alpha}_p}\right\|_2^2$$

## Solution

Repeat alternate estimation until the cost converges.




SPD (projector primary RGB)




Spectral reflectance (point ***p***)

Convergence Judgement

$$E\left(\boldsymbol{\alpha}^{k+1}, \boldsymbol{\beta}^{k+1}\right) - E\left(\boldsymbol{\alpha}^{k}, \boldsymbol{\beta}^{k}\right) < \sigma$$

$k$: iteration time

$\sigma$: threshold

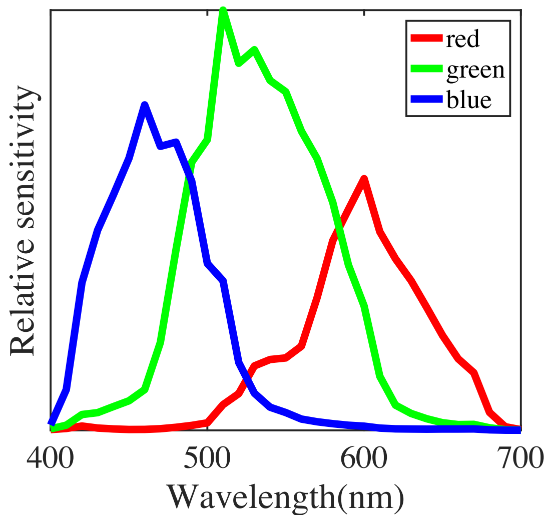
# Experiments

## Setup

- **Camera**

  Cannon 5D Mark II

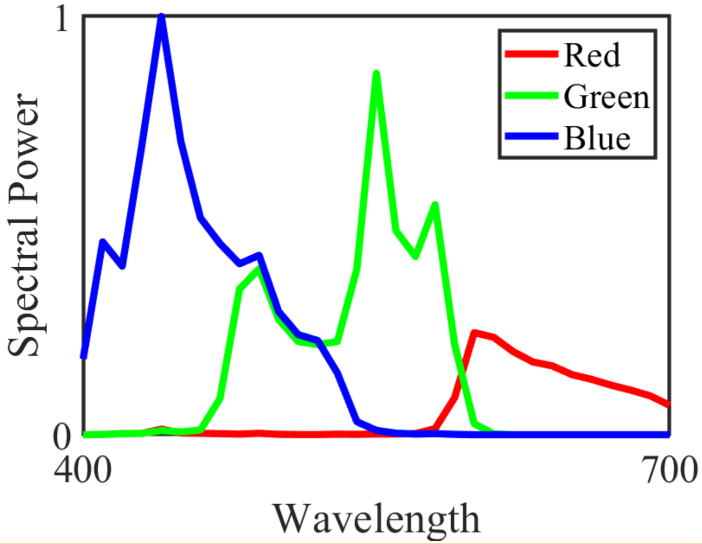
  (camera sensitivity is already known from other paper)




- **Projector**

  Casio XJ-SC21

  Mercury lamp DLP projector



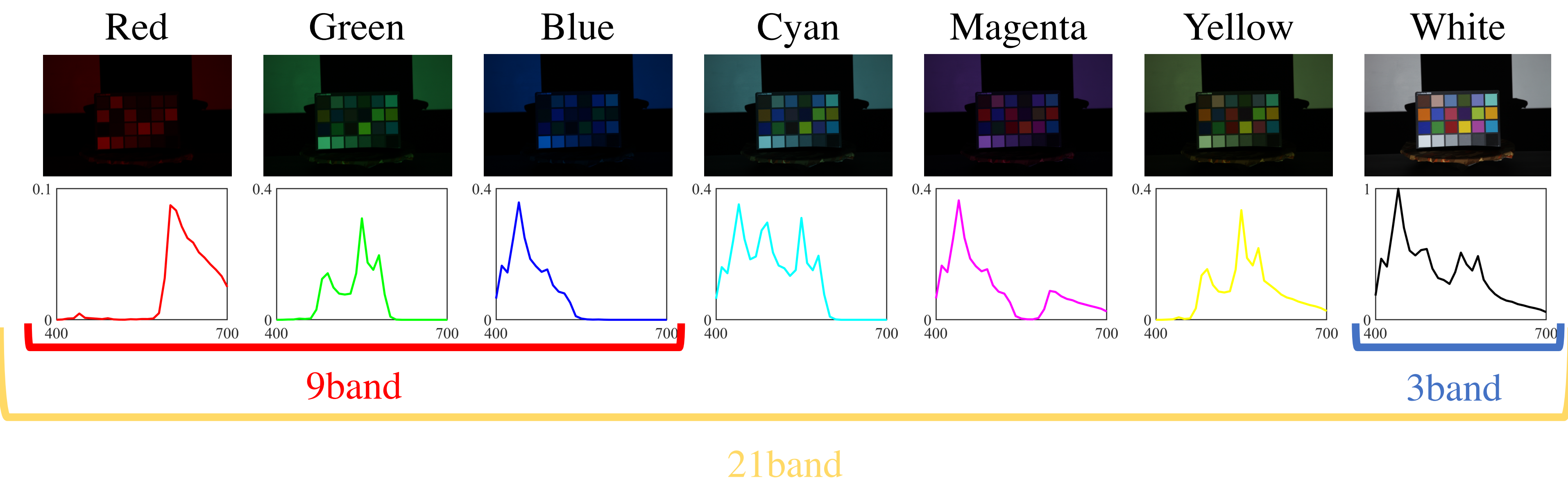
# Experiments

## Target Object

- Macbeth Color Chart 18 chromatic patches (Real Image)

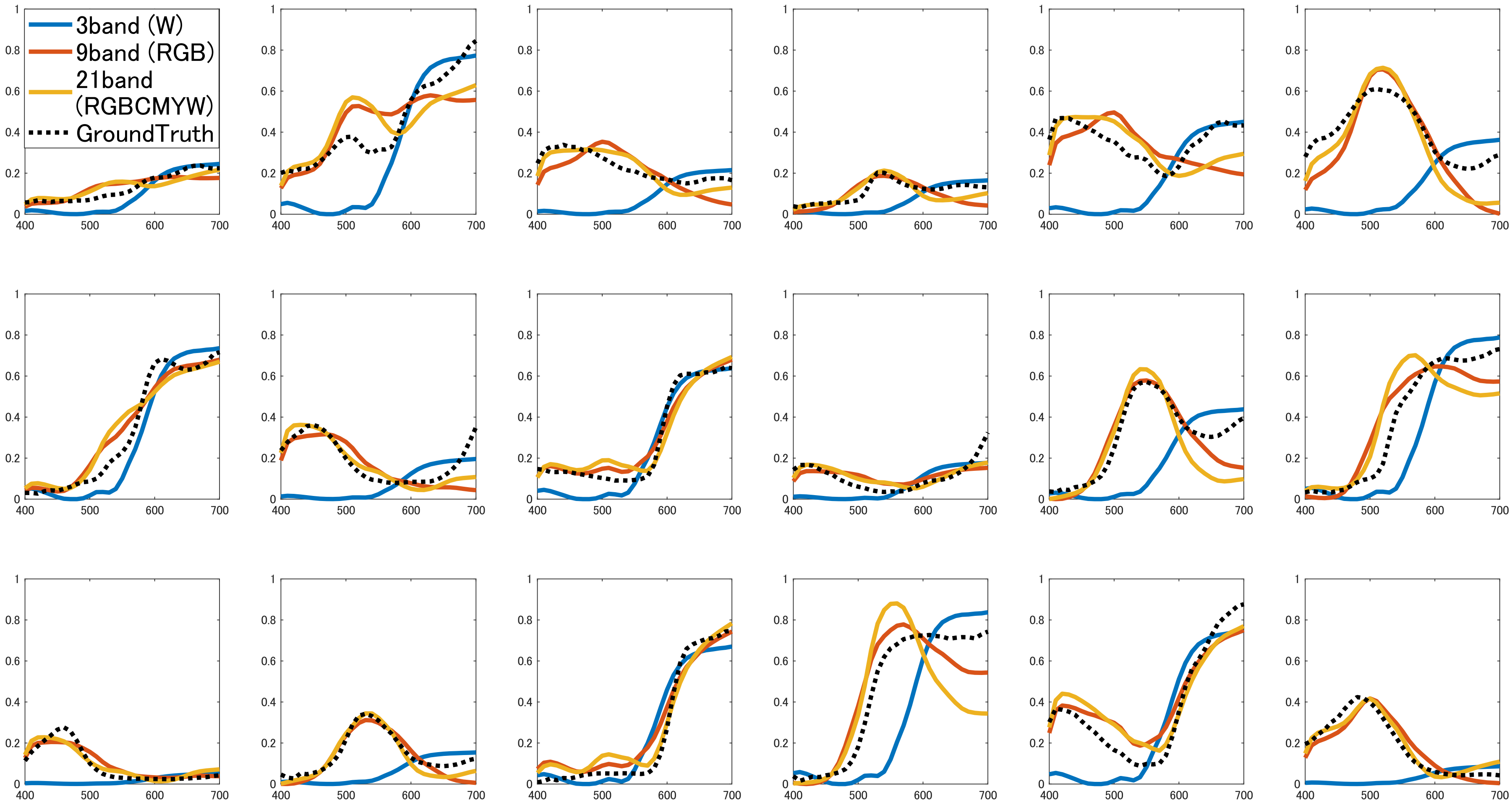
➢ Capture 7 images under Red, Green, Blue,  Cyan, Magenta, Yellow, and White light

## Input Images



# Spectral Reflectance Result

## Spectral Reflectance



# Spectral Reflectance Result

## Spectral Reflectance RMSE Table

Table 1: RMSE result for each patch of the colorchart

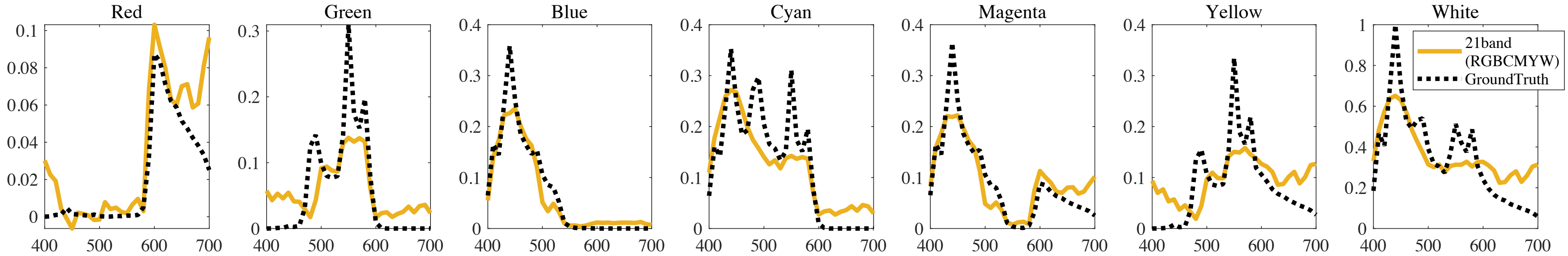
| Patch | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| 3band | 0.046 | 0.074 | 0.122 | 0.185 | 0.186 | 0.149 | 0.203 | 0.076 | 0.087 | 0.077 |
| 9band | 0.036 | **0.064** | 0.033 | 0.133 | 0.089 | 0.046 | 0.081 | **0.051** | 0.069 | 0.047 |
| 21band | **0.035** | 0.083 | **0.031** | **0.131** | **0.066** | **0.036** | **0.045** | 0.063 | **0.058** | **0.037** |

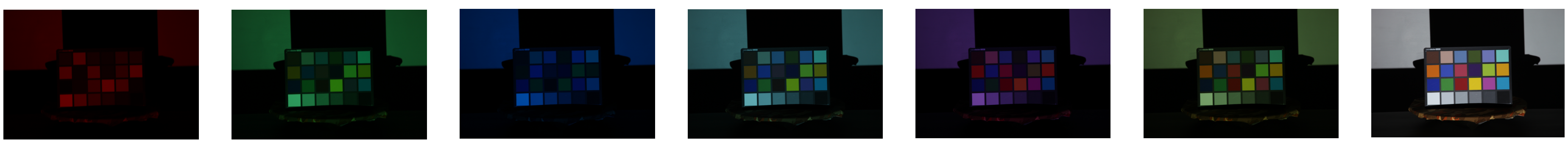
| Patch | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | Average |
|---|---|---|---|---|---|---|---|---|---|
| 3band | 0.083 | 0.225 | 0.261 | 0.232 | 0.181 | 0.366 | 0.142 | 0.227 | 0.1620 |
| 9band | 0.050 | **0.115** | 0.135 | **0.089** | 0.091 | 0.131 | **0.105** | 0.052 | 0.0787 |
| 21band | **0.041** | 0.210 | **0.102** | 0.132 | **0.086** | **0.116** | 0.143 | **0.036** | **0.0785** |

- RMSE for each patch is almost the same whether you use 3 or 7 images. We think it is because each case projected the linear combination of primary colors and  the amount of input information is not changed.

# SPD Result

## Spectral power distribution (SPD)



Red Green Blue Cyan Magenta Yellow White

# Conclusion

- We create a dataset of the spectral power distribution (SPD) of the projector and make a model for projector SPDs by basis functions

- It was shown that even if the spectral power distribution (SPD) of the projector is unknown, it is possible to estimate the spectral reflectance and SPD at the same time to some extent.