Supplementary Materials
What is the Space of Spectral Sensitivity Functions for Digital Color Cameras?

Jun Jiang† Dengyu Liu† Jinwei Gu† Sabine Süsstrunk‡
† Rochester Institute of Technology, ‡Ecole Polytechnique Fédérale de Lausanne

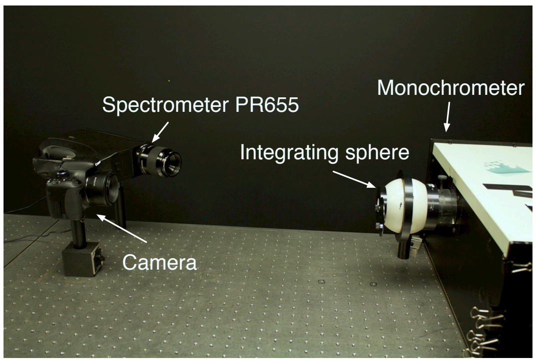


Figure 1. Experimental setup to obtain the ground truth of camera spectral sensitivity.

1. Experimental Setup to Measure the Ground Truth of Camera Spectral Sensitivity

As shown in Fig. 1, we have measured the spectral sensitivity functions for 28 cameras, including professional DSLRs, point-and-shoot, industrial and mobile cameras (*i.e.*Nokia N900), using a monochromator and a spectrometer PR655. At each wavelength, the camera spectral sensitivity in RGB channels is calculated by $c(\lambda) = d(\lambda)/(r(\lambda) \cdot t(\lambda))$, where d is the raw data recorded by the camera, r is the illuminant radiance measured by the spectrometer, and t is the exposure time of the camera. All other settings (*i.e.*, ISO and aperture) remained the same during the measurement for each camera. The procedure is repeated across the whole visible wavelength from 400 to 720nm with an interval of 10nm.

2. Recovery of Camera Spectral Sensitivity Using Other Basis Functions

To fully evaluate the recovery performance using eigenvectors extracted from camera spectral sensitivities, we compared the recovery by using other basis functions. Zhao et al. [2] tested three basis functions besides camera space eigenvectors, and they are polynomial, Fourier, and radial basis functions. Zhao et al. [2] concluded that radial basis functions are the best.

The equation for the basis functions can be found here [2]. However, for completeness, these equations are listed in the paper. The equation for the Fourier basis function is expressed as

$$\mathbf{F} = \sum_{i=0}^{D} a_i \cdot \sin(i\lambda\pi), \tag{1}$$

where λ is the wavelength vector normalized to be between 0 and 1. The Fourier basis functions are shown in Fig. 2(a).

The polynomial basis function is expressed as

$$\mathbf{F} = \sum_{i=0}^{D} a_i \cdot \lambda^i, \tag{2}$$

where λ is the wavelength vector from 400nm to 720nm with an interval of 10nm. It is normalized to be between 0 and 1. The recovered spectral sensitivity, $\mathbf{F}$ is a linear combination of λ^i. The polynomial basis functions are shown in Fig. 2(b).

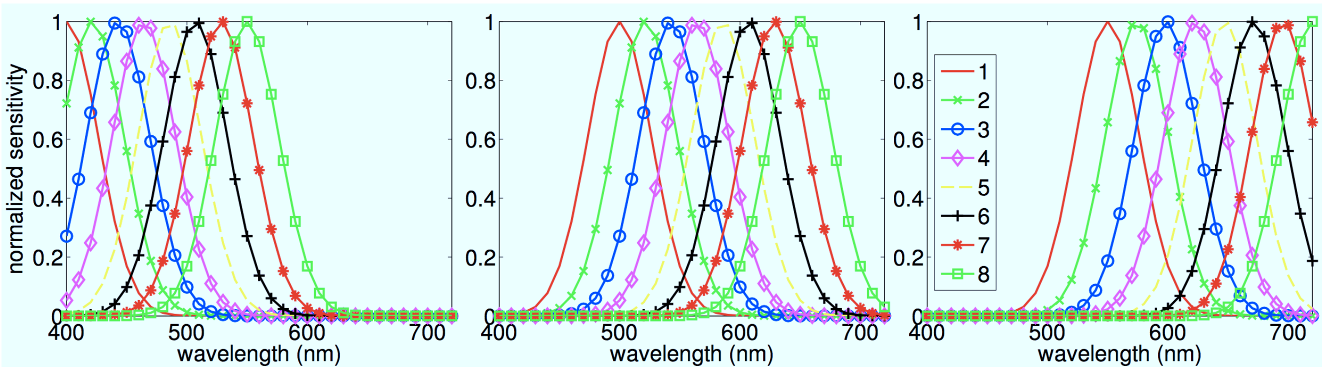
The radial basis functions are expressed as

$$\mathbf{F} = \sum_{i=0}^{D} a_i \cdot \exp(-\frac{(\lambda - \mu_i)^2}{\sigma^2}), \tag{3}$$

where λ is the wavelength vector normalized to be between 0 and 1. μ_i and σ^2 are the peak wavelength and the variance of each basis function. The radial functions are shown in Fig. 3(a), (b) and (c) for the red, green, and blue channels. Eight basis functions are selected for the polynomial, Fourier, and radial method [2].

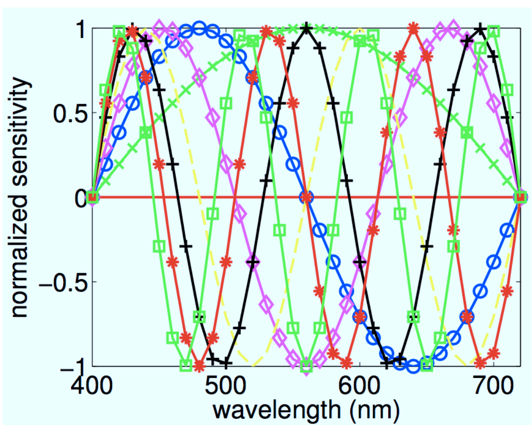
3. Robustness of Spectral Sensitivity Recovery to Daylight Variation

Judd [1] proposed that the daylight spectrum can be well represented using only a few parameters. To fully evaluate our recovery of camera spectral sensitivity under daylight, we simulated radiance using daylight measured at different time of the day, based on which the camera spectral sensitivity is recovered. The measured and recovered camera spectral sensitivity was then compared and spectral RMS calculated. The mean RMS for all 28 cameras in the database

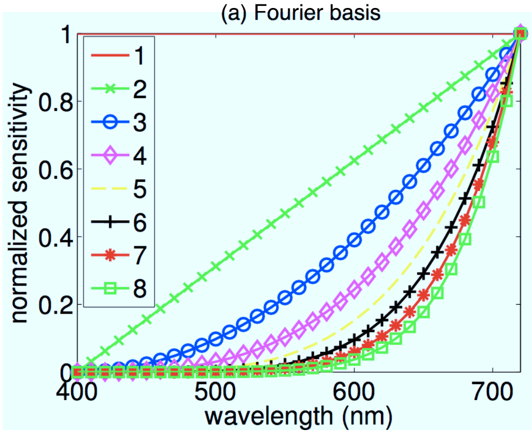


(a) Radial basis (blue)　(b) Radial basis (green)　(c) Radial basis (red)

Figure 3. The radial basis functions of the (a) red, (b) green, and (c) blue channel.

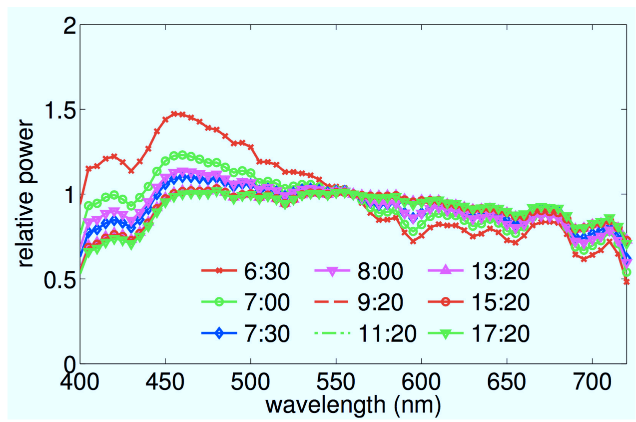


(a) Fourier basis

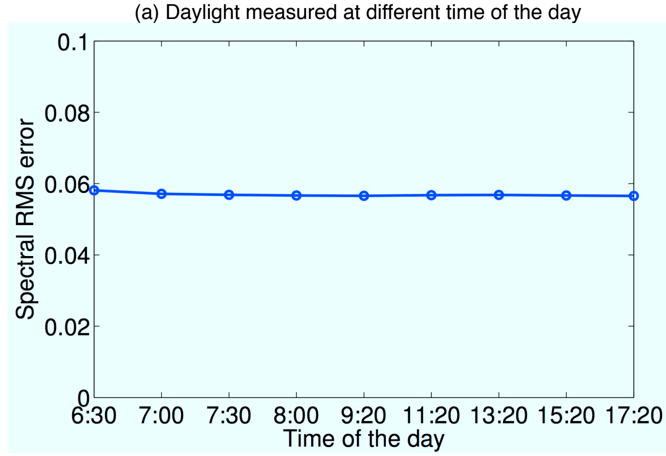


(b) Polynomial basis

Figure 2. The Fourier basis and polynomial basis functions.



(a) Daylight measured at different time of the day



(b) Recovery accuracy at different time of the day

Figure 4. The spectral RMS error between the recovered and measured camera spectral sensitivity at different time of the day.

is in Fig. 4. The recovery accuracy is about 0.06, almost invariant to daylight at different time of the day.

4. Dimensionality of Spectral Sensitivity

While the camera spectral sensitivity is of high dimension (*i.e.*33 if the wavelength ranges from 400nm to 720nm with an interval of 10nm), it can be represented using much fewer parameters. The variance that can be explained given the number of eigenvectors retained in the model is shown in Fig. 5. With two eigenvectors, we found that the camera spectral sensitivity can be well represented.

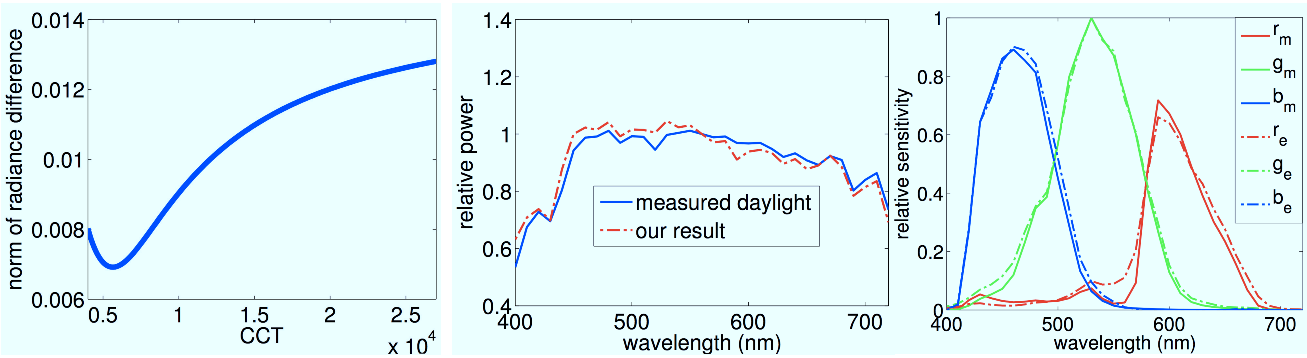


Figure 6. The recovery of the camera spectral sensitivity of NikonD3 using a single picture of CCDC under unknown daylight. (a) The radiance error given the estimated camera spectral sensitivity at a certain CCT. The daylight spectrum that yields the lowest radiance difference is plotted in (b) and compared with the ground truth. (c) The measured and recovered camera spectral sensitivity of NikonD3. The subscripts $_m$ and $_e$ stand for the measured and estimated camera spectral sensitivity.

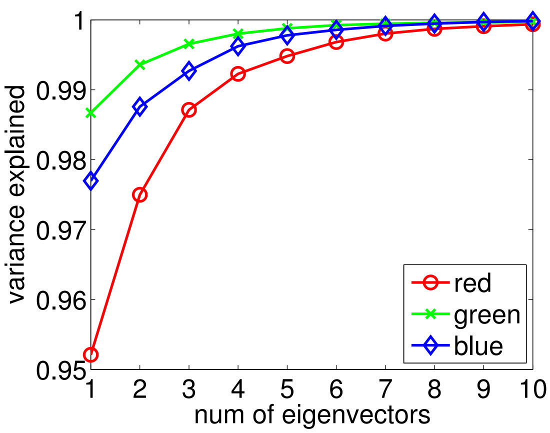


Figure 5. The percentage of total variance of the camera spectral sensitivity explained given the number of eigenvectors retained in the model. The first two eigenvectors are found to be enough to represent the space of camera spectral sensitivity.

5. Results on Spectral Sensitivity Recovery

We recovered the camera spectral sensitivity of NikonD3 using a picture of CCDC under unknown daylight. The radiance error given the CCT of daylight is in Fig. 6(a). The daylight spectrum that yields the least radiance eror is selected, and it is plotted in Fig. 6(b) with the measured daylight spectrum. A close match can be found between our recovered daylight and the ground truth. The recovered and measured camera spectral sensitivity are shown in Fig. 6(c). Similarly, the camera spectral sensitivity of a smartphone camera, NokiaN900, and another DSLR, Canon5D Mark II are recovered in Fig. **??**.

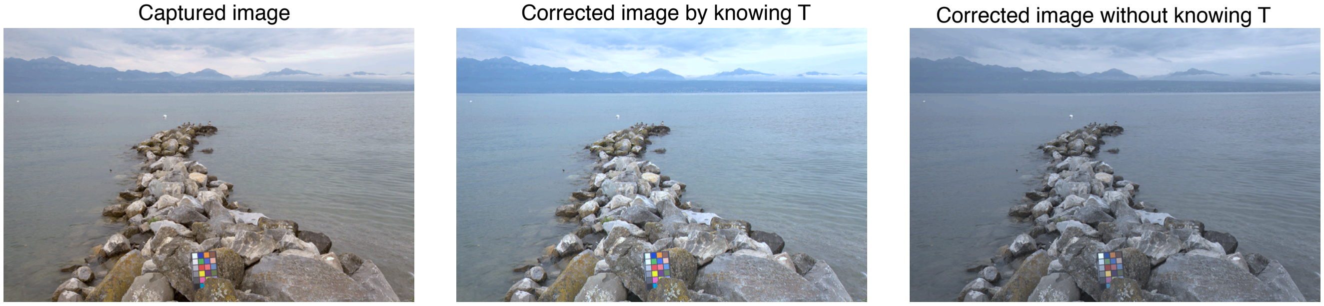
6. Results on Computational Color Constancy

Accurate color corrections of images can be made by knowing the camera spectral sensitivity. In order to recover the correct color of a scene, camera raw data needs to be converted to device-independent XYZ by Eq. (5) in the paper, and then a chromatic adaptation transform (*i.e.*a linear Bradford transform) is used to take care of the difference in the white point. Computational color constancy relies on the accurate estimation of $\mathbf{T}$ (by Eq. (5)) and the white point of the scene. Knowing camera spectral sensitivity can help estimate $\mathbf{T}$ correctly. Examples are shown in Fig. 8. The color cast in the captured images in Fig. 8 is removed successfully by knowing $\mathbf{T}$ estimated from the recovered camera spectral sensitivity of Canon 5D MarkII. On the other hand, the corrected images are less saturated by dividing the white point (without knowing the $\mathbf{T}$ matrix).

References

[1] Deaane B. Judd. Spectral distribution of typical daylight as a function of correlated color temperature. *Journal of the Optical Society of America*, 54:1031–1040, 1964. 1

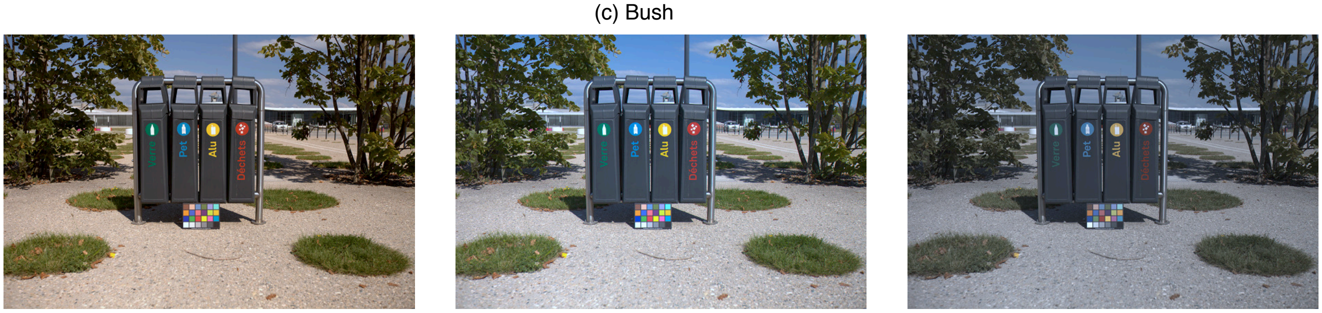
[2] Hongxun Zhao, Rei Kawakami, Robby T. Tan, and Katsushi Ikeuchi. Estimating basis functions for spectral sensitivity of digital cameras. *Meeting on Image Recognition and Understanding 2009*, 2009. 1



(a) Lake

(b) Grass

(c) Bush



(d) Trash cans

Figure 8. The correction of images by Canon5D Mark II by removing the color cast in the image. CC is put in the scene to locate the white point. The estimated camera spectral sensitivity of Canon5D Mark II is used to calculate $\mathbf{T}$ by Eq. (5). **Left column:** The captured image; **Middle column:** the corrected image based on $\mathbf{T}$, and **Right column:** the corrected image by dividing the white point (without using $\mathbf{T}$). The images are rendered in sRGB color space.