Digital color cameras - 2 - Spectral response

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Abstract

This report describes the spectral calibration of two digital color cameras, the Kodak DCS-200 and the Kodak DCS-420. We used previous work to model the output of the cameras in terms of the spectral sensitivities of the color sensors. We took measurements of the camera output for narrow-band spatially uniform scenes and used this data to estimate the sensor spectral sensitivities. The estimated spectral sensitivities were used to generate predicted RGB values which were compared to the measurements. The error between the predicted and measured values is a measure of the accuracy of the sensitivity estimates. For our estimates, this error is comparable to our estimates of the camera response variability. We also used the sensor estimates to predict the response of the DCS-200 to an independently acquired image. This prediction error was also small.

1 Introduction

To process data from digital color cameras, it is often necessary to know the spectral response properties of the camera's sensors. For example, many demosaicing [1], color correction [13] and illuminant estimation algorithms [4, 5] require this knowledge. In addition, the intrinsic color quality of an image depends on the spectral characteristics of the sensors [2, 7, 12, 14, 15] used. Thus an important component of characterizing a digital color camera is measuring its sensor spectral response functions.

We describe calibration of the spectral response of two color cameras, a Kodak DCS-200 and a Kodak DCS-420. The calibration procedure is based on the response models we developed previously for these cameras [10]. We use the resulting estimates in work where we simulate camera responses [9, 11].

The report is organized as follows. Section 2 describes the calibration data we collected. Sections 3 and 4 describe two different procedures for estimating the camera sensor spectral response functions. These are the *simple estimation* procedure and the *Wiener estimation* procedure respectively. Section 5 examines how well our estimates of the DCS-200 can predict the camera responses for images of the Macbeth ColorChecker Chart (MCC). Section 6 presents conclusions.

2 Methods

In a companion report [10], we showed that the following equation relates the output of a camera sensor r to the spectral response of the sensor $s(\lambda)$, the incident radiant power $i(\lambda)d\lambda$, the exposure time e and the measurement noise n:

$$r \;=\; \mathcal{F}(e\int_{\lambda_l}^{\lambda_h} s(\lambda)i(\lambda)d\lambda \;+\; n) \tag{1}$$

The wavelengths λ_l and λ_h are the limits beyond which the spectral response of the sensor is zero. The function $\mathcal{F}$ is a static non-linearity. We determined this function empirically for the DCS-420. For the DCS-200, the function is simply the identity.

We measured the spectral response functions for two color CCD cameras, the Kodak DCS-200 and Kodak DCS-420. For both cameras, we used the 8-bit acquisition software provided by Kodak. In this mode, the response of the DCS-200 is linear with intensity while the response of the DCS-420 is non-linear [10]. The camera apertures were kept fixed through all the experiments reported here, at f4 for the DCS-420 and f5.6 for the DCS-200. These are the same aperture settings we used to determine the camera response models.

To calibrate the camera spectral sensitivities, we measured camera responses to narrow band illumination. We created narrow band stimuli using light from a tungsten source passed through a monochromater (Bausch and Lomb, 1350 grooves/mm) and imaged onto a white reflectance standard (PhotoResearch RS-2). We measured the integrated radiance of each narrow band stimulus using a spectraradiometer (PhotoResearch PR-650). The camera and the radiometer were placed at similar geometric positions with respect to the reflectance standard.

It is difficult to measure the exact spectral power distributions of narrow band sources using the PR-650, since the instrument itself has a bandwidth of 8nm, comparable to that of the narrow band lights. When we performed calculations that required an estimate of the spectral power distributions, we modeled them as gaussians with a standard deviation of 7.5 nm and scaled so that they had the same integrated radiance as our measurements.

We extracted red, green, and blue (R, G, and B) sensor responses from the camera images and averaged these over a rectangular section in the center of the image (64×64 pixels for the DCS-420 and 30×25 pixels for the DCS-200).

For the DCS-200, we excluded measurements outside of the camera's linear operating range

- i.e. response values below 20 or above 240. We corrected the measured responses for the camera dark current by subtracting our estimate of its mean value (13.6 response units). For the DCS-420, we used the method described in the companion report [10] to obtain linearized response values.

To extend the dynamic range of the cameras, we varied the exposure duration across measurements. We normalized response data across exposure setting by dividing the measured response by the response duration. Thus the units of our calibrations are response per second of exposure. Where we had multiple measurements for the same incident illuminant, we used the data corresponding to the maximum non-saturated response. Tables 7 - 9 and Tables 10 - 12 in the appendix provide the response data we used for each camera.

3 Simple Estimates

To perform calculations, we write a sampled version of equation (1) that describes the entire calibration data set. Let **r**, **g**, and **b** be vectors representing the R, G, B readings to a series of narrowband lights. The vectors **r**, **g**, and **b** have K_r, K_g and K_b entries respectively, one for each of the narrowband stimuli used to calibrate the corresponding sensor. Let the full spectrum of the i^{th} narrowband light be $s_i(\lambda)$, and let the unknown camera spectral sensitivities be $c_r(\lambda)$, $c_g(\lambda)$ and $c_b(\lambda)$. From equation (1) we have,

$$\mathbf{r} \;=\; \mathcal{F}\Bigg(\begin{bmatrix} e(1)\sum_j c_r(\lambda_l + j\Delta\lambda)s_1(\lambda_l + j\Delta\lambda)\Delta\lambda \\ \vdots \\ e(i)\sum_j c_r(\lambda_l + j\Delta\lambda)s_i(\lambda_l + j\Delta\lambda)\Delta\lambda \\ \vdots \\ e(K_r)\sum_j c_r(\lambda_l + j\Delta\lambda)s_{K_r}(\lambda_l + j\Delta\lambda)\Delta\lambda \end{bmatrix} \;+\; \mathbf{n}\Bigg) \tag{2}$$

where **n** is a vector representing measurement noise with variation about the average dark noise value, $\Delta\lambda$ is the wavelength sampling for the radiometric measurements, and $e(i)$ is the exposure setting for the i^{th} measurement. The function $\mathcal{F}$ is applied pointwise to each component of the vector it acts on. It is the identity for the DCS-200 and the calibrated

static non-linearity for the DCS-420. Equations similar to the one above can be written for the readings **g** and **b**.

The equations for $c_r(\lambda)$, $c_g(\lambda)$ and $c_b(\lambda)$ may be solved in a number of different ways. In the rest of this section and in the following section we discuss two possibilities.

The illumination incident on the camera is narrow-band. This fact may be used to approximate equation (2) by

$$\mathbf{r} \;=\; \mathcal{F}\Bigg(\begin{bmatrix} e(1)c_r(\lambda_1)\sum_j s_1(\lambda_l + j\Delta\lambda)\Delta\lambda \\ \vdots \\ e(i)c_r(\lambda_i)\sum_j s_i(\lambda_l + j\Delta\lambda)\Delta\lambda \\ \vdots \\ e(K_r)c_r(\lambda_{K_r})\sum_j s_{K_r}(\lambda_l + j\Delta\lambda)\Delta\lambda \end{bmatrix} \;+\; \mathbf{n}\Bigg)$$

where λ_i is the wavelength of the peak of the i^{th} incident illumination. By ignoring the noise variability, we estimate the sensor response function $c_r(\lambda_i)$ as

$$c_r(\lambda_i) \;=\; \frac{\mathcal{F}^{-1}(r_i) \;-\; \bar{n}}{e(i)\sum_j s_i(\lambda_l + j\Delta\lambda)\Delta\lambda} \tag{3}$$

where r_i is the i^{th} component of $\mathbf{r}$, the quantity $\sum_j s_i(\lambda_l + j\Delta\lambda)\Delta\lambda$ is the integrated radiance of the i^{th} narrowband stimulus and $\bar{n}$ is the mean of the noise. For CCD cameras, this mean is typically non-zero.

Equation (3) is the 'simple' estimate of Hubel et al [3]. The function $\mathcal{F}$ is the identity for the DCS-200 and $\bar{n} \;=\; 13.6$ from the experiments detailed in [10]. For the DCS-420, the quantity $\mathcal{F}^{-1}(\mathbf{r}_i) \;-\; \bar{n}$ may be obtained from the calibration curve provided in [10].

Figure 1 shows plots of the simple estimates obtained for the DCS-200 and Figure 2 those for the DCS-420. The plotted estimates are interpolated from the raw estimates to a 5 nm wavelength spacing in the range 380 nm to 780 nm. In the interpolation procedure, values for wavelengths outside the range where we had data were set to zero. Tables 13 and 14 provided in the appendix tabulate the estimated sensor responses.

The expression

$$\mathcal{F}(e(i) \sum c_r(\lambda_j) s_i(\lambda_j) \Delta\lambda_j \ + \ \bar{n}) \tag{4}$$

was used to calculate RGB values for sensors with the estimated spectral sensitivities. The function $\mathcal{F}$ was taken to be the identity for the DCS-200. For the DCS-420, an inverse curve based on the previous calibration was used. We compared the predicted RGB values to the measurements. Figure 3 shows plots of the measured R, G and B values against the values indicated by expression (4) for the DCS-200, while Figure 4 shows the same for the DCS-420. Table 1 shows the statistics of the estimation error for the DCS-200 and Table 2 for the DCS-420. In these tables absolute error denotes the absolute value of the difference between measured and predicted values. The standard deviation of the camera dark noise is listed for comparison with the rms error associated with the sensor estimates.

Table 1: Statistics of Estimation Error - DCS-200 - Simple Estimate. RMS value of variation from linearity of DCS-200 is 1.45 [10].

Sensor Type	Mean of Absolute Error	Mean of Absolute % Error	RMS Error	Camera Noise Std. Deviation	Maximum Absolute Error	Maximum Absolute % Error
Red	1.34	1.60	3.68	0.88	16.46	20.27
Green	0.53	1.10	0.99	0.89	4.09	1.09
Blue	0.50	1.29	0.89	0.90	3.48	9.50

Table 2: Statistics of Estimation Error - DCS-420 - Simple Estimate. RMS value of variation from modelling curve of DCS-420 is 0.50 [10].

Sensor Type	Mean of Absolute Error	Mean of Absolute % Error	RMS Error	Camera Noise Std. Deviation	Maximum Absolute Error	Maximum Absolute % Error
Red	0.83	0.88	1.59	0.49	7.47	6.00
Green	0.57	0.88	0.74	0.47	1.96	4.17
Blue	0.59	0.91	0.78	0.47	2.36	3.99

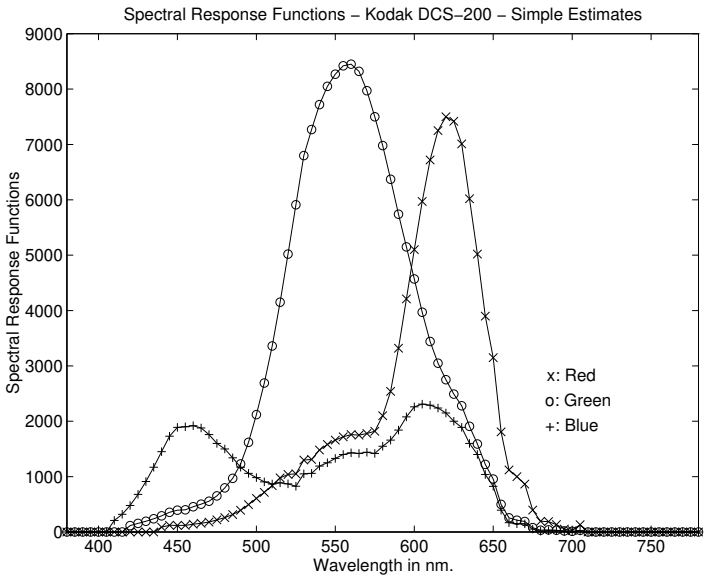

Figure 1: Spectral Response Functions of the Kodak DCS-200 - Simple Estimate.

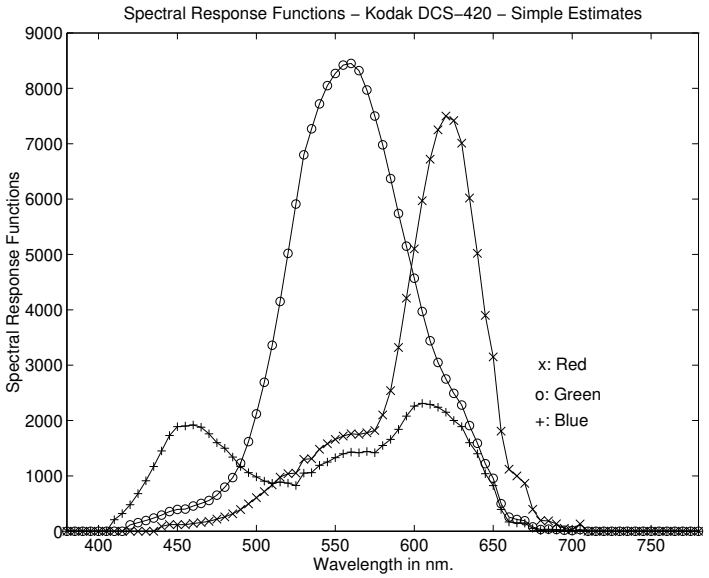

Figure 2: Spectral Response Functions of the Kodak DCS-420 - Simple Estimate.

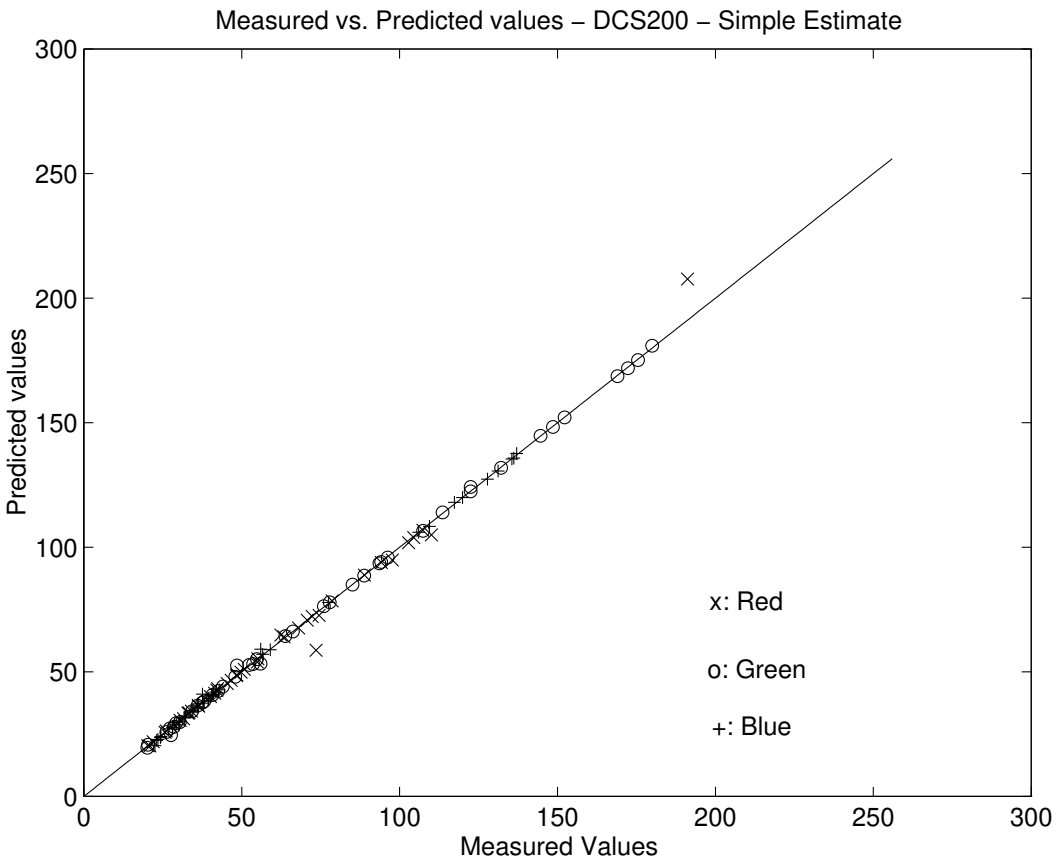

Figure 3: Measured vs. Predicted Values Kodak DCS-200 - Simple Estimate.

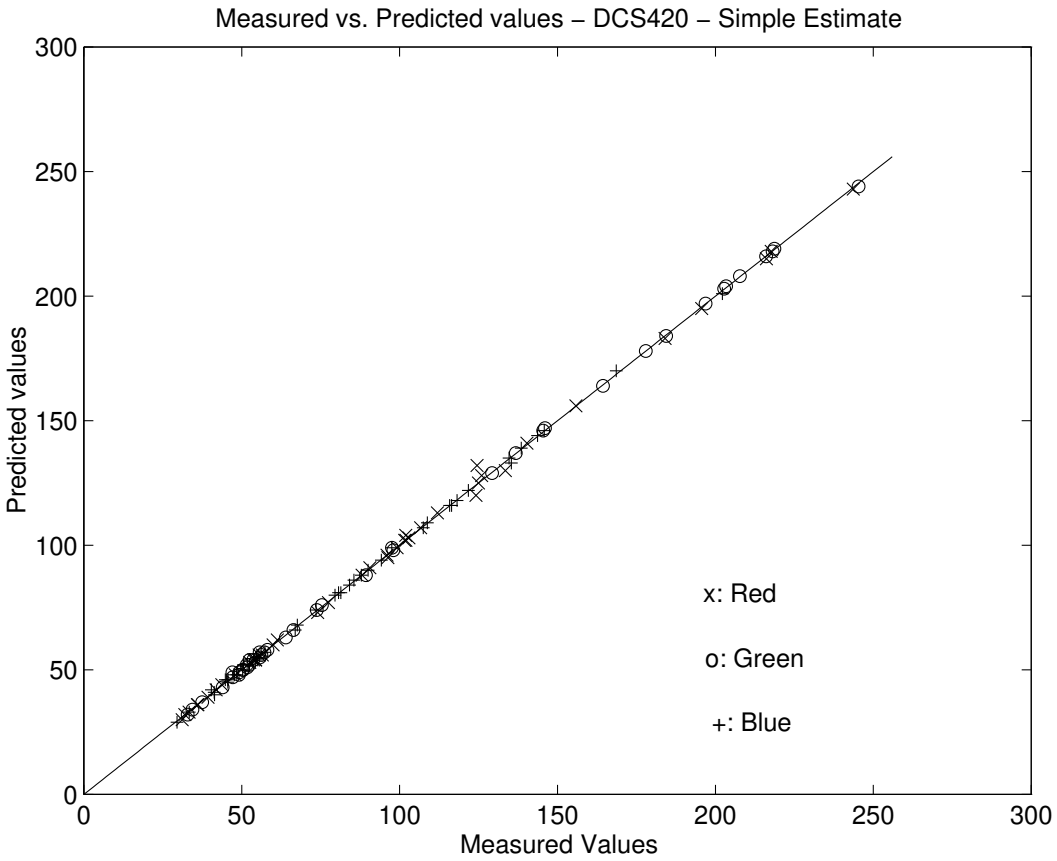

Figure 4: Measured vs. Predicted Values Kodak DCS-420 - Simple Estimate.

4 Wiener Estimates

The simple estimation procedure neglects the variability in the sensor responses. It also neglects the fact that the width of the spectral power distribution of the narrowband light source is non-zero. Error in the response measurement for a narrowband light at one wavelength directly affects the sensitivity estimate for that wavelength, as does error in the measure of the power of the incident light. It is possible to employ more sophisticated estimation techniques that take camera response variability (noise variation) and the non-zero width of the spectral power distribution of incident light into account when producing the estimates. In this section, we describe how we used Wiener estimation to obtain a second set of sensor estimates.

We begin by rewriting the equation to be solved (equation 2) in matrix form. Let $\mathbf{y}$ represent the linearized and normalized sensor measurements for a particular sensor. That is, let the i^{th} entry of $\mathbf{y}$ be $\mathbf{y}_i = \frac{\mathcal{F}^{-1}(r_i) - \bar{n}}{e(i)}$. Let $\mathbf{x}$ be a vector representing the sensor estimate to be obtained represented at discrete sample wavelengths. We can write $\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}_0$ where $\mathbf{H}$ is a matrix whose i^{th} row is the sampled spectrum of the i^{th} narrowband stimulus and $\mathbf{n}_0$ is a vector representing zero-mean additive noise. Our goal is to solve this system of linear equations for $\mathbf{x}$. This is a standard problem. Pratt [6] provides the Wiener estimate for problems of this form. We used a variant of this procedure that is guaranteed to produce all positive estimates.

The Wiener procedure requires that we regard the quantity to be estimated ($\mathbf{x}$) as a gaussian random variable with known mean and covariance. We took the mean $\bar{\mathbf{x}}$ to be the simple estimate obtained in the previous section and constructed the covariance matrix $\kappa_{\mathbf{x}}$ by assuming that $\mathbf{x}$ was the result of a first-order discrete Gauss-Markov process whose variance was equal to the variance of the entries of $\bar{\mathbf{x}}$ and whose entry-to-entry correlation was equal to the correlation between neighboring entries of $\bar{\mathbf{x}}$. We assumed that the entries of $\mathbf{n}_0$ were

independently and identically distributed with mean zero and variance equal to 2% of the maximum linearized sensor response (after correction for non-linearity, mean noise level, and exposure duration). We did this for each sensor.

The DCS-200 estimates are plotted in Figure 5, the predicted RGB values in Figure 7 and the error statistics are listed in Table 3. The DCS-420 estimates are plotted in Figure 6, the predicted RGB values in Figure 8 and the error statistics listed in Table 4. The plotted estimates are interpolated from the raw estimates to a 5 nm wavelength spacing in the range 380 nm to 780 nm. In the interpolation procedure, values for wavelengths outside the range where we had data were set to zero. Tables 15 and 16 provided in the appendix tabulate the estimated sensor responses.

Table 3: Statistics of Estimation Error - DCS-200 - Wiener Estimates. RMS value of variation from linearity of DCS-200 is 1.45 [10].

Sensor Type	Mean of Absolute Error	Mean of Absolute % Error	RMS Error	Noise Std. Deviation	Maximum Absolute Error	Maximum Absolute % Error
Red	0.53	0.65	1.42	0.88	8.07	4.22
Green	0.57	0.55	0.46	0.89	1.34	2.65
Blue	0.28	0.62	0.41	0.90	1.58	4.20

Table 4: Statistics of Estimation Error - DCS-420 - Wiener Estimates. RMS value of variation from modelling curve of DCS-420 is 0.50 [10].

Sensor Type	Mean of Absolute Error	Mean of Absolute % Error	RMS Error	Noise Std. Deviation	Maximum Absolute Error	Maximum Absolute % Error
Red	0.40	0.51	0.62	0.49	2.47	3.69
Green	0.35	0.55	0.46	0.47	1.34	2.65
Blue	0.47	0.66	0.59	0.47	1.50	2.63

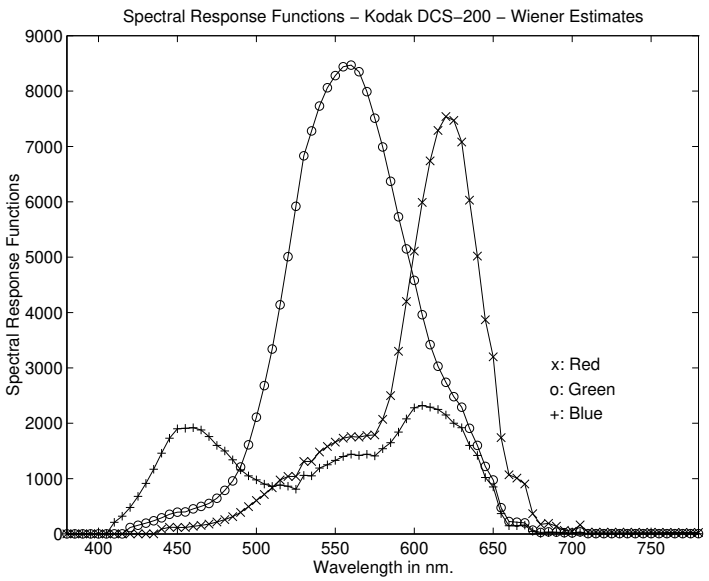

Figure 5: Spectral Response Functions of the Kodak DCS-200 - Wiener Estimate.

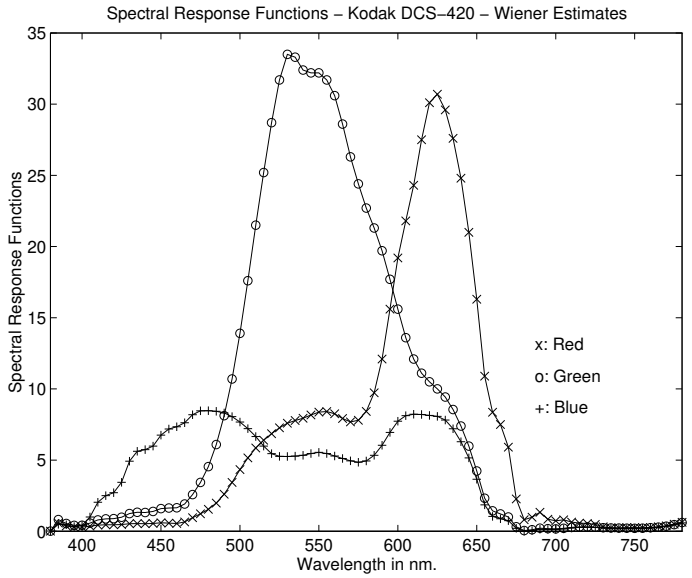

Figure 6: Spectral Response Functions of the Kodak DCS-420 - Wiener Estimate.

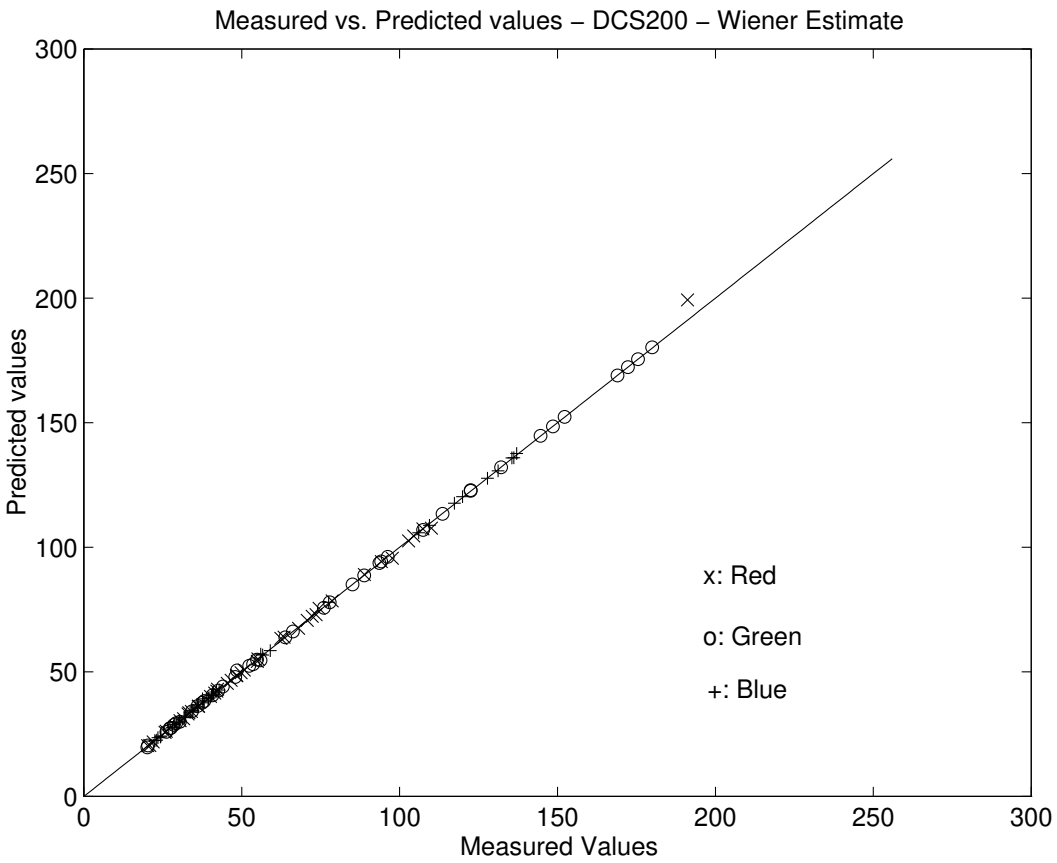

Figure 7: Measured vs. Predicted Values Kodak DCS-200 - Wiener Estimate.

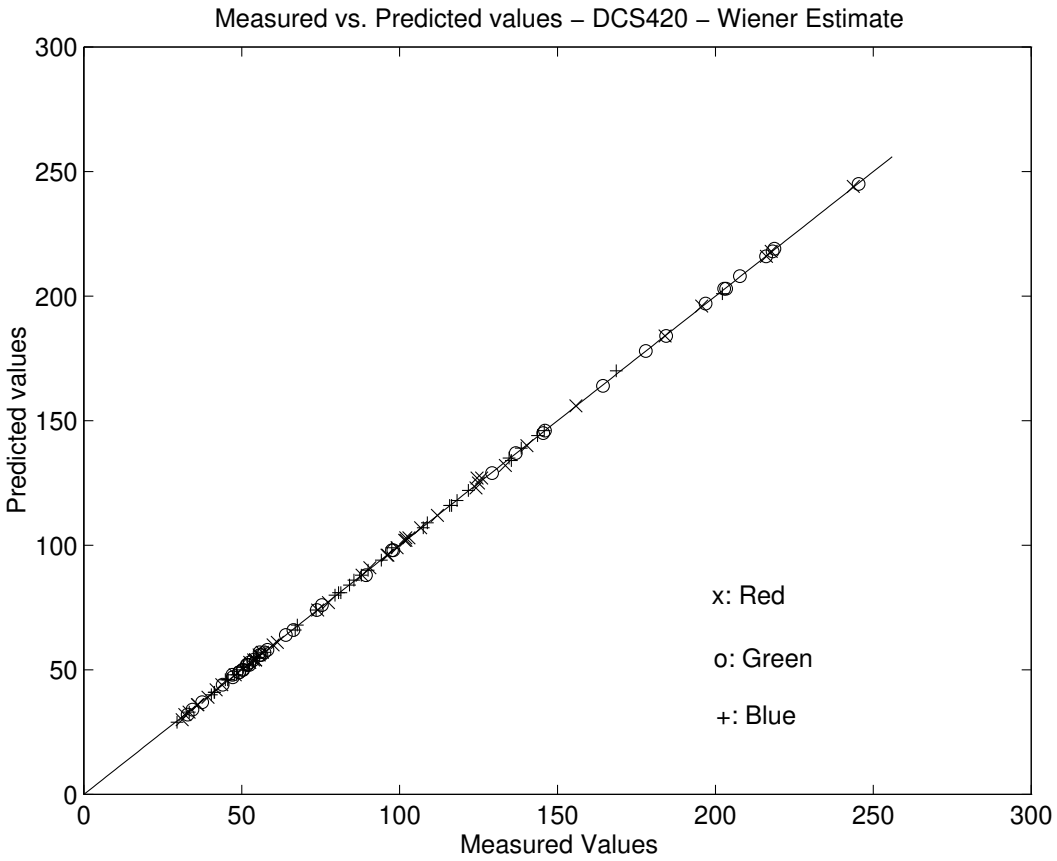

Figure 8: Measured vs. Predicted Values Kodak DCS-420 - Wiener Estimate.

The error for the Wiener estimate is very low and close to the rms value predicted by the noise statistics for both cameras. It may be compared to the far higher error in [3]. Presumably one factor driving the small error is that we used many narrowband lights to calibrate the sensors. Also, since we used narrowband lights, the simple and the Wiener estimates are very similar. This would not have been so if we had used broadband lights.

Non-linear estimation methods like Projections Onto Convex Sets (POCS) [8] are used when the Wiener estimation method gives results that clearly do not satisfy prior knowledge of the solution. For example, POCS would be used if the Wiener estimates gave unreasonable errors in the RGB values. Our Wiener estimate satisfies the three known constraints: the set of measured and predicted RGB values agree leaving room for reasonable noise, the filters are reasonably smooth, the filter transmissivities are non-negative. Hence, we did not attempt non-linear (particularly constrained) estimation methods.

5 Verification of Estimates

For the DCS-200, we tested the spectral sensitivity estimates by collecting two images of the MCC under a tungsten illuminant. For one image we used an exposure duration of $\frac{1}{30}$ second and for the other a duration of $\frac{1}{15}$ second. We compared the actual R, G, and B responses for the 24 color checker patches with values predicted from the spectral sensitivities and direct radiometric measurements of the light reaching the camera from each patch. To calculate the actual R, G, and B responses we averaged a roughly 20 $\times$ 20 pixel region at the center of each patch. The radiometric measurements were taken with the PhotoResearch PR-650 placed at approximately the same position as the camera. Figures 9 and 10 show the predicted vs. measured values for the simple and Wiener estimates respectively. Tables 5 and 6 list the prediction errors for the simple and Wiener estimates. The tables also list the standard deviation of the camera dark noise as well as the rms value of the variation of measured values within the 20 $\times$ 20 pixel region over which measurements were averaged.

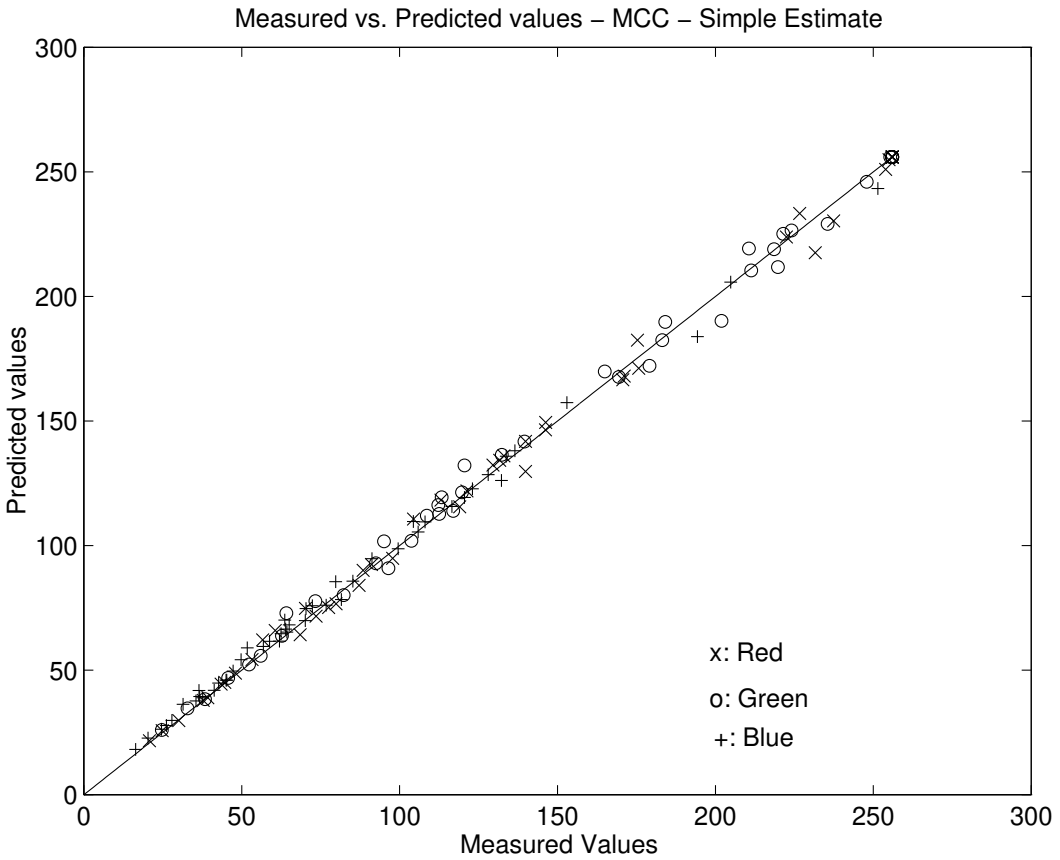

Figure 9: Measured vs. Predicted Values for MCC - Kodak DCS-200 - Simple Estimate.

Table 5: Statistics of Estimation Error for MCC - DCS-200 - Simple Estimates. RMS value of variation from linearity of DCS-200 is 1.45 [10].

Sensor Type	Mean of Absolute Error	Mean of Absolute % Error	RMS Error	RMS of Variation in Patch	Camera Noise Std. Deviation	Maximum Absolute Error	Maximum Absolute % Error
Red	2.76	2.58	3.99	2.08	0.88	14.12	9.72
Green	2.84	2.40	4.25	1.96	0.89	11.78	13.59
Blue	2.74	4.55	3.56	1.83	0.90	10.44	15.53

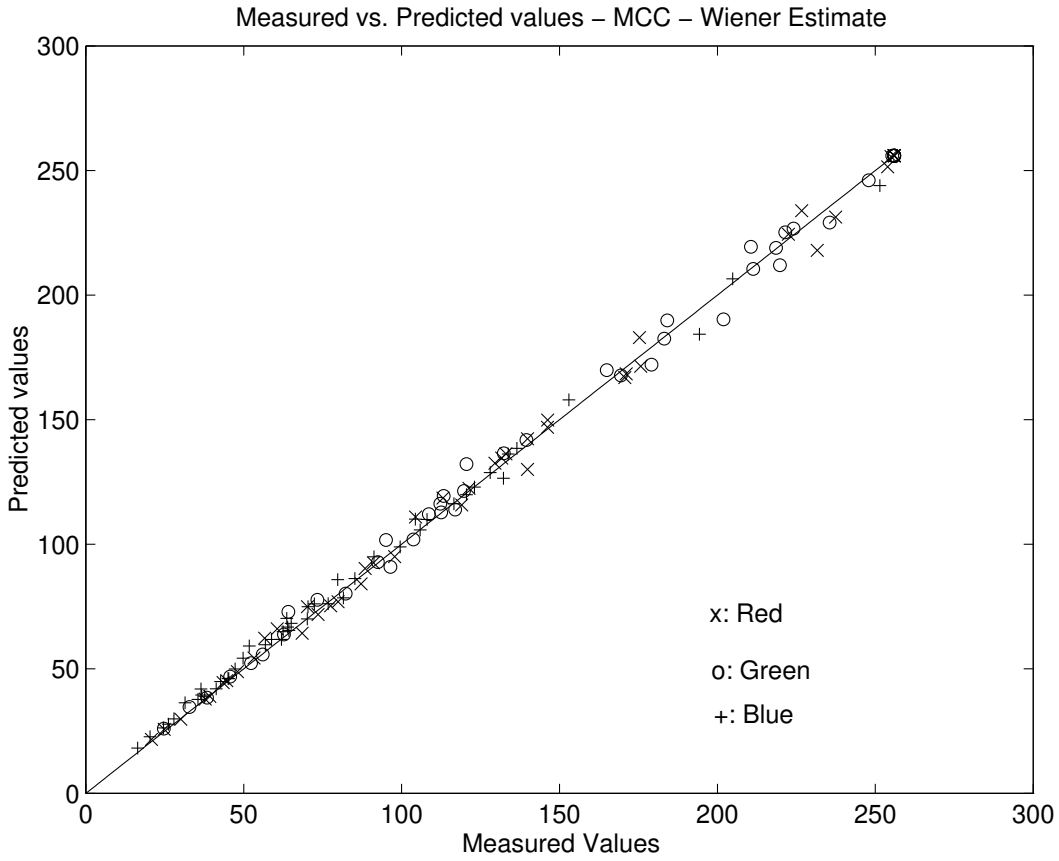

Figure 10: Measured vs. Predicted Values Kodak DCS-200 - Wiener Estimate.

Table 6: Statistics of Estimation Error for MCC - DCS-200 - Wiener Estimates. RMS value of variation from linearity of DCS-200 is 1.45 [10]

Sensor Type	Mean of Absolute Error	Mean of Absolute % Error	RMS Error	RMS of Variation in Patch	Camera Noise Std. Deviation	Maximum Absolute Error	Maximum Absolute % Error
Red	2.80	2.63	3.97	2.08	0.88	13.63	9.97
Green	2.85	2.41	4.27	1.96	0.89	11.70	13.63
Blue	2.81	4.68	3.60	1.83	0.90	9.95	15.80

6 Conclusions

We have calibrated the spectral sensitivities of two digital color cameras. Both simple and Wiener estimates of these sensitivities yielded low mean square errors when they were used to predict the calibration data set. Higher but still small errors were obtained when the estimates for the DCS-200 were used to predict the average RGB values over patches in images of the MCC. The performance of the estimates is good enough for us to use them with confidence in a digital camera simulator. There is no significant difference between the two types of estimates, largely due to the fact that we used narrowband light sources for the calibration.

Appendix

Tables 7 - 9 list the set of measurements used to calibrate the DCS-200. For each sensor, the first column gives the wavelength of the monochromatic light, the second the integrated radiance of the light, the third the exposure duration, the fourth the measured response and the last the response of the camera sensor normalized by the exposure duration.

Tables 10 - 12 list the set of measurements used to calibrate the DCS-420. The columns are as in the DCS-200 measurements, in addition, the last column gives the linearized response of the camera sensor normalized by the exposure duration. Wavelengths are rounded to the nearest 5 nm increment.

Tables 13 and 14 list the simple sensor estimates and Tables 15 and 16 the Wiener sensor estimates for the DCS-200 and the DCS-420 respectively.

Table 7: Response data for DCS-200: Red sensor.

Peak Wavelength (nm)	Radiance (0.01 watts/sr/m2)	Exposure (sec)	Raw Response	Exposure Corrected
440	1.05	8.0	20.9	0.911
450	1.27	8.0	25.7	1.51
455	1.40	4.0	20.2	1.66
460	1.49	4.0	22.0	2.09
470	1.74	4.0	26.1	3.12
475	1.93	4.0	30.5	4.22
480	1.96	4.0	34.1	5.12
490	2.22	4.0	48.4	8.71
500	2.35	4.0	70.8	14.3
510	2.48	2.0	55.1	20.8
520	2.61	2.0	68.0	27.2
525	2.73	1.0	42.4	28.8
530	2.76	0.5	31.6	36.0
535	3.00	0.5	33.3	39.4
540	3.07	0.5	36.4	45.5
545	3.35	0.5	40.1	53.1
550	3.35	0.5	41.4	55.7
555	3.69	0.5	45.4	63.6
560	3.76	0.5	46.7	66.2
565	3.97	0.5	48.4	69.5
570	4.06	0.5	49.8	72.4
575	4.27	0.25	33.0	77.6
580	4.31	0.25	36.2	90.5
585	4.49	0.25	42.1	114
590	4.48	0.25	50.8	149
600	4.60	0.25	72.3	235
610	4.80	0.25	94.2	323
620	5.00	0.25	107.4	375
625	4.90	0.25	104.5	363
630	5.09	0.25	102.8	357
635	5.00	0.25	88.8	301
640	5.19	0.25	78.6	260
645	5.11	0.25	63.4	199
650	5.26	0.25	55.0	165
655	5.39	0.5	62.4	97.6
670	5.57	2.0	110.1	48.2
675	5.60	8.0	191.2	22.2
685	5.62	8.0	97.7	10.5
690	5.64	8.0	74.5	7.61
705	5.69	8.0	73.6	7.49

Table 8: Response data for DCS-200: Green sensor.

Peak Wavelength (nm)	Radiance (0.01 watts/sr/m2)	Exposure (sec)	Raw Response	Exposure Corrected
420	0.706	8.0	20.10	0.813
430	0.876	8.0	27.22	1.70
440	1.05	8.0	38.12	3.07
450	1.27	8.0	53.60	5.00
455	1.40	4.0	36.04	5.61
460	1.49	4.0	40.72	6.78
470	1.74	4.0	52.39	9.70
475	1.93	4.0	63.81	12.6
480	1.96	2.0	76.02	15.6
490	2.22	2.0	122.50	27.2
500	2.35	1.0	113.58	50.0
510	2.48	0.5	179.98	83.2
520	2.61	0.5	144.63	131
525	2.73	0.5	94.14	161
530	2.76	0.25	107.41	188
535	3.00	0.25	122.48	218
540	3.07	0.25	132.15	237
545	3.35	0.25	148.57	270
550	3.35	0.25	152.25	277
555	3.69	0.25	169.01	311
560	3.76	0.25	172.27	317
565	3.97	0.25	96.20	330
570	4.06	0.3	175.47	324
575	4.27	1.0	93.62	320
580	4.31	2.0	88.77	301
585	4.49	2.0	85.08	286
590	4.48	4.0	77.87	257
600	4.60	4.0	66.22	210
610	4.80	8.0	54.84	165
620	5.00	8.0	47.93	137
625	4.90	8.0	44.04	122
630	5.09	8.0	42.58	116
635	5.00	4.0	37.49	95.6
640	5.19	4.0	34.26	82.6
645	5.11	4.0	29.24	62.5
650	5.26	1.0	26.18	50.3
655	5.39	0.5	20.32	26.9
670	5.57	0.25	55.94	10.6
675	5.60	0.25	48.49	4.36
685	5.62	0.25	30.42	2.10
690	5.64	0.25	28.50	1.86
705	5.69	0.25	27.60	1.75

Table 9: Response data for DCS-200: Blue sensor.

Peak Wavelength (nm)	Radiance (0.01 watts/sr/m2)	Exposure (sec)	Raw Response	Exposure Corrected
410	0.570	8.0	23.08	1.19
420	0.706	8.0	40.67	3.38
430	0.876	8.0	77.54	7.99
440	1.05	8.0	135.55	15.2
450	1.27	4.0	109.47	24.0
455	1.40	4.0	119.93	26.6
460	1.49	4.0	127.80	28.5
470	1.74	4.0	136.15	30.6
475	1.93	4.0	137.06	30.9
480	1.96	2.0	131.18	29.4
490	2.22	2.0	117.33	25.9
500	2.35	2.0	106.02	23.1
510	2.48	1.0	56.63	21.5
520	2.61	0.5	59.02	22.7
525	2.73	0.5	36.14	22.5
530	2.76	0.25	28.08	29.0
535	3.00	0.25	29.43	31.7
540	3.07	0.25	31.83	36.5
545	3.35	0.25	34.56	41.9
550	3.35	0.25	35.88	44.6
555	3.69	0.25	39.37	51.5
560	3.76	0.25	40.53	53.9
565	3.97	0.25	41.82	56.4
570	4.06	0.5	42.84	58.5
575	4.27	2.0	28.81	60.8
580	4.31	2.0	30.26	66.6
585	4.49	4.0	32.23	74.5
590	4.48	4.0	34.26	82.6
600	4.60	8.0	39.60	104
610	4.80	8.0	41.06	110
620	5.00	8.0	40.45	107
625	4.90	8.0	38.11	98.0
630	5.09	4.0	37.72	96.5
635	5.00	4.0	33.64	80.2
640	5.19	4.0	31.75	72.6
645	5.11	1.0	26.87	53.1
650	5.26	0.5	24.43	43.3
655	5.39	0.5	24.14	21.2
670	5.57	0.5	30.07	8.24
675	5.60	0.25	37.58	3.00
685	5.62	0.25	24.25	1.33
690	5.64	0.25	23.45	1.23
705	5.69	0.25	22.52	1.11

Table 10: Response data for DCS-420: Red Sensor.

Peak Wavelength (nm)	Radiance (watts/sr/m2)	Exposure (sec)	Raw Response	Linear Response	Exposure Corrected
385	0.0019	8	31.15	0.009	0.0011
390	0.0034	8	32.00	0.010	0.0013
405	0.0043	8	33.33	0.012	0.0015
410	0.0052	8	36.12	0.018	0.0022
425	0.0063	8	39.30	0.024	0.0030
430	0.0078	8	43.69	0.033	0.0041
445	0.0094	8	47.95	0.041	0.0051
450	0.0113	8	53.79	0.054	0.0068
465	0.0133	2	35.97	0.018	0.0089
470	0.0156	2	41.90	0.030	0.0150
480	0.0188	2	55.50	0.059	0.0293
490	0.0208	2	77.49	0.109	0.0545
500	0.0220	2	102.97	0.190	0.0950
510	0.0229	2	124.95	0.267	0.1340
520	0.0244	1	96.02	0.167	0.1670
530	0.0268	1	106.62	0.203	0.2030
540	0.0189	1	90.55	0.150	0.1500
550	0.0212	1	99.19	0.177	0.1770
560	0.0227	1	101.99	0.187	0.1870
570	0.0242	1	101.62	0.187	0.1870
580	0.0257	1	111.99	0.219	0.2190
590	0.0264	1	140.31	0.322	0.3220
600	0.0272	1	184.08	0.520	0.5200
610	0.0284	1	217.67	0.692	0.6920
620	0.0295	1	243.63	0.882	0.8820
630	0.0231	1	216.15	0.681	0.6810
640	0.0235	1	195.65	0.579	0.5790
650	0.0238	1	155.83	0.387	0.3870
655	0.0243	1	125.99	0.270	0.2700
670	0.0523	1	133.49	0.297	0.2970
675	0.0529	2	124.53	0.267	0.1340
690	0.0532	4	124.18	0.263	0.0658
695	0.0531	4	101.93	0.187	0.0468
705	0.0536	4	96.31	0.167	0.0418
710	0.0539	4	88.09	0.141	0.0353
725	0.0536	4	74.05	0.101	0.0253
730	0.0535	4	61.25	0.070	0.0174
745	0.0528	4	54.40	0.054	0.0135
750	0.0509	4	52.53	0.052	0.0130
760	0.0499	4	54.40	0.054	0.0135
770	0.0433	4	59.95	0.067	0.0169
780	0.0247	4	56.51	0.061	0.0152

Table 11: Response data for DCS-420: Green Sensor.

Peak Wavelength (nm)	Radiance (watts/sr/m2)	Exposure (sec)	Raw Response	Linear Response	Exposure Corrected
385	0.0019	8	32.87	0.012	0
390	0.0034	8	34.38	0.015	0
405	0.0043	8	37.49	0.02	0
410	0.0052	8	43.97	0.033	0
425	0.0063	8	52.41	0.05	0.01
430	0.0078	8	63.99	0.077	0.01
445	0.0094	8	75.42	0.104	0.01
450	0.0113	8	89.32	0.144	0.02
465	0.0133	2	52.50	0.052	0.03
470	0.0156	2	66.40	0.082	0.04
480	0.0188	2	97.56	0.173	0.09
490	0.0208	2	145.44	0.341	0.17
500	0.0220	2	203.37	0.613	0.31
510	0.0229	1	177.94	0.491	0.49
520	0.0244	1	218.67	0.698	0.70
530	0.0268	1	245.31	0.891	0.89
540	0.0189	1	202.76	0.613	0.61
550	0.0212	1	216.05	0.681	0.68
560	0.0227	1	218.12	0.692	0.69
570	0.0242	1	207.74	0.638	0.64
580	0.0257	1	196.87	0.584	0.58
590	0.0264	1	184.37	0.520	0.52
600	0.0272	1	164.37	0.424	0.42
610	0.0284	1	146.03	0.345	0.35
620	0.0295	1	136.76	0.311	0.31
630	0.0300	1	129.27	0.282	0.28
640	0.0235	1	98.02	0.173	0.17
650	0.0238	1	73.78	0.101	0.10
655	0.0243	1	55.66	0.059	0.06
670	0.0523	1	51.77	0.050	0.05
675	0.0529	2	47.04	0.038	0.02
690	0.0532	4	49.14	0.043	0.01
695	0.0531	4	47.17	0.038	0.01
705	0.0536	4	50.48	0.045	0.01
710	0.0539	4	56.25	0.059	0.01
725	0.0536	4	57.21	0.061	0.02
730	0.0535	4	53.68	0.054	0.01
745	0.0528	4	50.26	0.045	0.01
750	0.0509	4	49.26	0.043	0.01
760	0.0499	4	51.58	0.050	0.01
770	0.0433	4	58.16	0.063	0.02
780	0.0247	4	55.75	0.059	0.01

Table 12: Response data for DCS-420: Blue Sensor.

Peak Wavelength (nm)	Radiance (watts/sr/m2)	Exposure (sec)	Raw Response	Linear Response	Exposure Corrected
385	0.0019	8	29.53	0.0070	0.0009
390	0.0034	8	33.41	0.0120	0.0015
405	0.0043	8	44.82	0.0340	0.0043
410	0.0052	8	66.96	0.0840	0.0105
425	0.0063	8	97.50	0.1730	0.0216
430	0.0078	8	135.36	0.3040	0.0380
445	0.0094	8	168.59	0.4480	0.0560
450	0.0113	8	202.23	0.6090	0.0761
465	0.0133	2	107.46	0.2030	0.1020
470	0.0156	2	121.77	0.2550	0.1280
480	0.0188	2	138.51	0.3180	0.1590
490	0.0208	2	145.82	0.3450	0.1730
500	0.0220	2	143.67	0.3370	0.1690
510	0.0229	2	134.68	0.3040	0.1520
520	0.0244	1	85.54	0.1340	0.1340
530	0.0268	1	87.88	0.1410	0.1410
540	0.0189	1	73.54	0.1010	0.1010
550	0.0212	1	79.55	0.1170	0.1170
560	0.0227	1	81.39	0.1200	0.1200
570	0.0242	1	80.65	0.1200	0.1200
580	0.0257	1	84.12	0.1280	0.1280
590	0.0264	1	94.20	0.1600	0.1600
600	0.0272	1	108.79	0.2090	0.2090
610	0.0284	1	115.86	0.2330	0.2330
620	0.0295	1	118.21	0.2400	0.2400
630	0.0300	1	116.44	0.2330	0.2330
640	0.0235	1	90.00	0.1470	0.1470
650	0.0238	1	67.61	0.0870	0.0865
655	0.0243	1	50.50	0.0480	0.0475
670	0.0523	1	45.57	0.0360	0.0363
675	0.0529	2	40.39	0.0260	0.0130
690	0.0532	4	41.42	0.0280	0.0070
695	0.0531	4	41.29	0.0280	0.0070
705	0.0536	4	45.64	0.0360	0.0091
710	0.0539	4	52.49	0.0500	0.0124
725	0.0536	4	54.68	0.0560	0.0141
730	0.0535	4	51.68	0.0500	0.0124
745	0.0528	4	48.47	0.0410	0.0102
750	0.0509	4	47.64	0.0410	0.0102
760	0.0499	4	50.30	0.0450	0.0113
770	0.0433	4	57.35	0.0610	0.0152
780	0.0247	4	55.08	0.0560	0.0141

Table 13: Simple Estimates - DCS-200.

Wavelength (nm)	Red (/watt/sr/m2/sec)	Green	Blue	Wavelength (nm)	Red (/watt/sr/m2/sec)	Green	Blue
380	0	0	0	580	2100	6980	1550
385	0	0	0	585	2540	6370	1660
390	0	0	0	590	3320	5740	1840
395	0	0	0	595	4210	5150	2080
400	0	0	0	600	5100	4570	2260
405	0	0	0	605	5970	3970	2310
410	0	0	208	610	6720	3440	2290
415	0	0	320	615	7250	3050	2240
420	0	115	479	620	7500	2750	2150
425	0	155	679	625	7420	2490	2000
430	0	194	912	630	7010	2280	1890
435	0	238	1170	635	6020	1910	1600
440	86.8	292	1450	640	5020	1590	1400
445	121	356	1730	645	3900	1220	1040
450	119	395	1890	650	3150	957	825
455	119	401	1900	655	1810	499	394
460	140	455	1920	660	1120	255	169
465	157	503	1880	665	1000	214	150
470	179	556	1760	670	866	190	148
475	219	651	1600	675	397	77.9	53.6
480	261	796	1500	680	193	31.9	15.6
485	316	970	1340	685	187	37.4	23.7
490	393	1230	1170	690	135	33.0	21.8
495	495	1620	1060	695	53.8	19.5	10.7
500	607	2120	982	700	25.5	13.3	4.99
505	715	2690	906	705	132	30.8	19.6
510	837	3360	868	710	0	0	0
515	977	4150	889	715	0	0	0
520	1040	5020	869	720	0	0	0
525	1050	5910	827	725	0	0	0
530	1300	6800	1050	730	0	0	0
535	1310	7270	1060	735	0	0	0
540	1480	7720	1190	740	0	0	0
545	1580	8050	1250	745	0	0	0
550	1660	8270	1330	750	0	0	0
555	1720	8420	1400	755	0	0	0
560	1760	8450	1430	760	0	0	0
565	1750	8320	1420	765	0	0	0
570	1780	7970	1440	770	0	0	0
575	1820	7500	1420	775	0	0	0
				780	0	0	0

Table 14: Simple Estimates - DCS-420.

Wavelength (nm)	Red (/watt/sr/m2/sec)	Green	Blue	Wavelength (nm)	Red (/watt/sr/m2/sec)	Green	Blue
380	0.00	0.00	0.00	580	8.52	22.7	4.98
385	0.565	0.807	0.476	585	9.86	21.3	5.38
390	0.368	0.539	0.445	590	12.2	19.7	6.06
395	0.288	0.410	0.324	595	15.6	17.7	6.92
400	0.293	0.419	0.408	600	19.1	15.6	7.68
405	0.354	0.566	0.995	605	21.8	13.7	8.08
410	0.427	0.789	2.03	610	24.4	12.1	8.20
415	0.453	0.870	2.49	615	27.5	11.2	8.20
420	0.453	0.882	2.70	620	29.9	10.5	8.14
425	0.473	0.988	3.44	625	30.5	10.0	8.04
430	0.527	1.24	4.90	630	29.5	9.40	7.77
435	0.538	1.33	5.60	635	27.5	8.51	7.16
440	0.526	1.32	5.73	640	24.6	7.36	6.26
445	0.544	1.39	5.99	645	21.0	5.96	5.12
450	0.598	1.59	6.74	650	16.3	4.24	3.63
455	0.578	1.65	7.17	655	11.1	2.41	1.95
460	0.556	1.68	7.35	660	8.47	1.48	1.10
465	0.665	1.95	7.63	665	7.37	1.21	0.871
470	0.958	2.62	8.17	670	5.68	0.950	0.694
475	1.24	3.47	8.44	675	2.52	0.363	0.246
480	1.56	4.60	8.46	680	1.02	0.0876	0.0319
485	2.00	6.15	8.42	685	1.02	0.116	0.0559
490	2.62	8.20	8.29	690	1.24	0.202	0.132
495	3.43	10.8	8.03	695	0.880	0.181	0.132
500	4.32	13.9	7.66	700	0.757	0.174	0.134
505	5.14	17.6	7.20	705	0.779	0.211	0.169
510	5.83	21.4	6.64	710	0.654	0.271	0.231
515	6.38	25.2	6.00	715	0.576	0.304	0.269
520	6.84	28.6	5.49	720	0.544	0.304	0.278
525	7.26	31.6	5.28	725	0.471	0.283	0.263
530	7.57	33.2	5.26	730	0.326	0.253	0.232
535	7.77	33.2	5.28	735	0.249	0.232	0.208
540	7.94	32.4	5.34	740	0.243	0.221	0.194
545	8.16	32.2	5.46	745	0.256	0.214	0.193
550	8.35	32.1	5.52	750	0.255	0.211	0.200
555	8.39	31.6	5.45	755	0.254	0.222	0.207
560	8.24	30.5	5.29	760	0.271	0.249	0.227
565	7.94	28.6	5.11	765	0.316	0.295	0.275
570	7.73	26.4	4.96	770	0.389	0.363	0.350
575	7.87	24.4	4.88	775	0.489	0.460	0.450
				780	0.614	0.592	0.570

Table 15: Wiener Estimates - DCS-200.

Wavelength (nm)	Red (/watt/sr/m2/sec)	Green	Blue	Wavelength (nm)	Red (/watt/sr/m2/sec)	Green	Blue
380	2.33	2.87	2.95	580	2070	6990	1540
385	2.37	2.89	3.00	585	2500	6370	1650
390	2.40	2.91	3.04	590	3300	5730	1840
395	2.44	2.93	3.08	595	4200	5150	2080
400	2.48	2.95	3.13	600	5110	4580	2280
405	2.52	2.97	3.17	605	5990	3960	2320
410	2.56	2.99	211	610	6740	3420	2290
415	2.61	3.01	322	615	7290	3030	2250
420	2.65	118	480	620	7540	2740	2150
425	2.69	158	680	625	7470	2480	2000
430	2.74	195	913	630	7080	2290	1920
435	2.78	238	1170	635	6030	1910	1600
440	89.5	292	1460	640	5020	1600	1420
445	122	356	1730	645	3870	1220	1020
450	120	395	1900	650	3200	975	850
455	118	399	1910	655	1740	475	368
460	139	453	1920	660	1070	226	149
465	156	499	1880	665	1010	213	150
470	178	551	1760	670	904	200	160
475	218	645	1600	675	367	70.7	46.3
480	259	788	1500	680	174	26.9	10.6
485	313	959	1340	685	192	38.5	25.1
490	390	1210	1160	690	140	34.5	23.2
495	494	1610	1050	695	67.0	22.5	13.0
500	606	2110	979	700	49.1	18.3	8.61
505	714	2680	902	705	164	37.3	24.3
510	836	3340	861	710	33.4	6.81	4.85
515	976	4140	884	715	32.9	6.77	4.78
520	1040	5010	863	720	32.4	6.72	4.71
525	1040	5920	810	725	31.9	6.67	4.64
530	1310	6830	1060	730	31.4	6.63	4.58
535	1310	7280	1050	735	30.9	6.58	4.51
540	1480	7730	1190	740	30.4	6.53	4.45
545	1580	8060	1250	745	29.9	6.49	4.38
550	1660	8280	1330	750	29.4	6.44	4.32
555	1730	8440	1400	755	28.9	6.40	4.26
560	1760	8470	1440	760	28.5	6.35	4.20
565	1750	8350	1420	765	28.0	6.31	4.14
570	1780	7990	1440	770	27.6	6.27	4.08
575	1790	7510	1410	775	27.1	6.22	4.02
				780	26.7	6.18	3.96

Table 16: Wiener Estimates - DCS-420.

Wavelength (nm)	Red (/watt/sr/m2/sec)	Green	Blue	Wavelength (nm)	Red (/watt/sr/m2/sec)	Green	Blue
380	0.00697	0.0104	0.0134	580	8.42	22.7	4.94
385	0.572	0.817	0.489	585	9.73	21.3	5.34
390	0.373	0.547	0.456	590	12.1	19.7	6.04
395	0.292	0.417	0.333	595	15.6	17.7	6.94
400	0.297	0.424	0.416	600	19.2	15.6	7.73
405	0.357	0.571	1.00	605	21.8	13.6	8.12
410	0.430	0.794	2.04	610	24.3	12.1	8.22
415	0.455	0.874	2.50	615	27.5	11.1	8.20
420	0.455	0.884	2.71	620	30.1	10.5	8.14
425	0.474	0.989	3.44	625	30.7	10.0	8.07
430	0.529	1.24	4.92	630	29.6	9.43	7.81
435	0.539	1.33	5.62	635	27.6	8.55	7.20
440	0.527	1.32	5.73	640	24.8	7.39	6.29
445	0.544	1.39	5.98	645	21.0	5.98	5.15
450	0.600	1.59	6.75	650	16.3	4.23	3.65
455	0.574	1.63	7.18	655	10.9	2.32	1.86
460	0.546	1.65	7.34	660	8.36	1.43	1.04
465	0.652	1.91	7.62	665	7.50	1.22	0.879
470	0.951	2.58	8.19	670	5.91	1.00	0.742
475	1.23	3.43	8.46	675	2.27	0.317	0.206
480	1.54	4.54	8.47	680	0.816	0.0490	-0.0001
485	1.98	6.09	8.43	685	0.989	0.109	0.05
490	2.60	8.12	8.31	690	1.33	0.219	0.145
495	3.43	10.7	8.05	695	0.843	0.179	0.132
500	4.33	13.9	7.67	700	0.740	0.168	0.129
505	5.15	17.6	7.21	705	0.803	0.208	0.165
510	5.85	21.5	6.65	710	0.646	0.275	0.234
515	6.40	25.2	5.98	715	0.571	0.308	0.274
520	6.85	28.7	5.45	720	0.550	0.307	0.282
525	7.27	31.7	5.26	725	0.482	0.284	0.265
530	7.59	33.5	5.25	730	0.315	0.251	0.231
535	7.78	33.3	5.28	735	0.240	0.231	0.206
540	7.94	32.4	5.34	740	0.240	0.220	0.193
545	8.17	32.2	5.46	745	0.259	0.214	0.191
550	8.37	32.2	5.54	750	0.255	0.209	0.200
555	8.41	31.7	5.46	755	0.252	0.219	0.205
560	8.25	30.6	5.29	760	0.267	0.246	0.223
565	7.92	28.6	5.11	765	0.311	0.290	0.270
570	7.68	26.3	4.95	770	0.385	0.359	0.346
575	7.80	24.4	4.85	775	0.497	0.468	0.458
				780	0.633	0.611	0.589

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List of Tables

1 Statistics of Estimation Error - DCS-200 - Simple Estimate. 5

2 Statistics of Estimation Error - DCS-420 - Simple Estimate. 5

3 Statistics of Estimation Error - DCS-200 - Wiener Estimates. 10

4 Statistics of Estimation Error - DCS-420 - Wiener Estimates. 10

5 Statistics of Estimation Error for MCC - DCS-200 - Simple Estimates. . . . 15

6 Statistics of Estimation Error for MCC - DCS-200 - Wiener Estimates. . . . 16

7 Response data for DCS-200: Red sensor. 18

8 Response data for DCS-200: Green sensor. 19

9 Response data for DCS-200: Blue sensor. 20

10 Response data for DCS-420: Red Sensor. 21

11 Response data for DCS-420: Green Sensor. 22

12 Response data for DCS-420: Blue Sensor. 23

13 Simple Estimates - DCS-200. 24

14 Simple Estimates - DCS-420. 25

15 Wiener Estimates - DCS-200. 26

16 Wiener Estimates - DCS-420. 27

List of Figures

1 Spectral Response Functions - Kodak DCS-200 - Simple Estimate. 6

2 Spectral Response Functions - Kodak DCS-420 - Simple Estimate. 6

3 Measured vs. Predicted Values - Kodak DCS-200 - Simple Estimate. 7

4 Measured vs. Predicted Values - Kodak DCS-420 - Simple Estimate. 8

5 Spectral Response Functions - Kodak DCS-200 - Wiener Estimate. 11

6 Spectral Response Functions - Kodak DCS-420 - Wiener Estimate. 11

7 Measured vs. Predicted Values - Kodak DCS-200 - Wiener Estimate. 12

8 Measured vs. Predicted Values - Kodak DCS-420 - Wiener Estimate. 13

9 Measured vs. Predicted Values for MCC - Kodak DCS-200 - Simple Estimate. 15

10 Measured vs. Predicted Values for MCC - Kodak DCS-200 - Wiener Estimate. 16