LINEAR MODELS FOR DIGITAL CAMERAS

Poorvi L. Vora, Joyce E. Farrell
Hewlett-Packard Laboratories,

Jerôme D. Tietz, David H. Brainard
Dept. of Psychology, University of California at Santa Barbara

Contact Address:
1501 Page Mill Road, Palo Alto, CA 94304
Phone: (415) 857-2457, Fax: (415) 857-4691
Email: poorvi@hpl.hp.com

Abstract

In this paper we describe methods for testing the linearity and estimating the spectral sensitivities of color sensors in digital cameras. We base our analysis on the response of the Kodak DCS-200 and DCS-420 digital cameras to calibrated spectral input. We use this data to build a linear model of the digital camera and verify it by comparing the actual camera response to calibrated spectral input to output values predicted by the linear model.

1 Introduction

The processing of digital color camera data (e.g. color correction, demosaicing, and image restoration) often depends on 1) the assumption that the camera sensor responses are linear with respect to source intensity and 2) apriori knowledge of the camera sensor spectral sensitivity. In this paper we describe methods for testing the camera linearity assumption and estimating the spectral sensitivity of the camera sensors.

2 Camera Linearity

The light sensors in many modern digital cameras are based on Charge-Coupled Device (CCD) or Active Pixel Sensor (APS) technology. These devices are known to have linear intensity-response functions over a wide operating range [1] and thus the response linearity assumption is plausible. The overall camera system may not exhibit the underlying device linearity, however. For example, there may be a non-linear mapping between the raw sensor output and the digital responses actually available from the camera. Such a non-linearity might be designed into a camera system if the dynamic range of the sensor itself is larger than that of the camera. This is the situation with the Kodak DCS-420. It employs a 12-bit internal data representation but its standard control software provides only 8-bits of precision.

To test the linearity of the camera response, we measured the intensity-response functions of the Kodak DCS-200 and the Kodak DCS-420 cameras. The DCS-200 contains an 8-bit CCD array while DCS-420 contains a 12-bit CCD array. For both cameras, images were obtained with a Macintosh host computer using 8-bit drivers provided by Kodak. The camera apertures were kept fixed (at f5.6 for the DCS-200 and at f4 for the DCS-420) for all experiments described in this report.

Our basic procedure was to take pictures of a white surface (PhotoResearch RS-2 reflectance standard) when it was illuminated by light of different intensities and different wavelengths. We illuminated the surface with light from a tungsten source passed through a grating monochrometer (Bausch & Lomb, 1350 grooves/mm) and varied the intensity by placing neutral density filters in the light path. We used a spectrophotometer (PhotoResearch PR-650) to measure directly the spectrum of the light reflected to the camera. Using this set-up, we measured camera intensity-response functions at several exposure durations for both the DCS-200 and DCS-420 cameras.

Both the DCS-200 and DCS-420 have a resolution of 1524 $\times$ 1012 and the RGB sensors for each camera are arranged in a Bayer mosaic pattern [2]. To obtain sensor data from the camera images we subsampled the camera output using this Bayer pattern. To estimate the mean value of the (dark) additive noise, we acquired images with the lens cap on the camera.

2.1 Camera response model for the Kodak DCS-200

The behavior of the Kodak DCS-200 can be described by a *linear response model.* For this model, the camera response for a pixel of the i^{th} sensor type pixel is given by

$$r_i \;=\; e\int_{\lambda_l}^{\lambda_h} s_i(\lambda)i(\lambda)d\lambda \;+\; n_i$$

where $s_i(\lambda)$ is the spectral sensitivity of the i^{th} sensor type, $i(\lambda)$ is the incident power density per unit time at wavelength λ, e is the exposure duration, and n_i is a normal random variable. Typically there are three sensor types (red, green, and blue) so that $i = 1,2,3$. The mean and variance of n_i describe the dark noise and response variability for the i^{th} sensor type. The limits λ_l and λ_h are the wavelength limits beyond which the spectral response of the sensor is zero.

Our data indicate that the linear response model describes the output of the Kodak DCS-200, at least over most of its operating range. Figure 1 shows the calibration line obtained from assuming a linear model and additive dark noise and marked points representing normalized intensity response plotted as a function of the camera DAC output. DAC values were normalized by subtracting the dark noise (DAC value recorded when the lens cap was on) and scaling it by the highest linear camera response and exposure duration. This normalization procedure was done for data collected at different exposures and with illumination at different intensities and wavelengths [3].

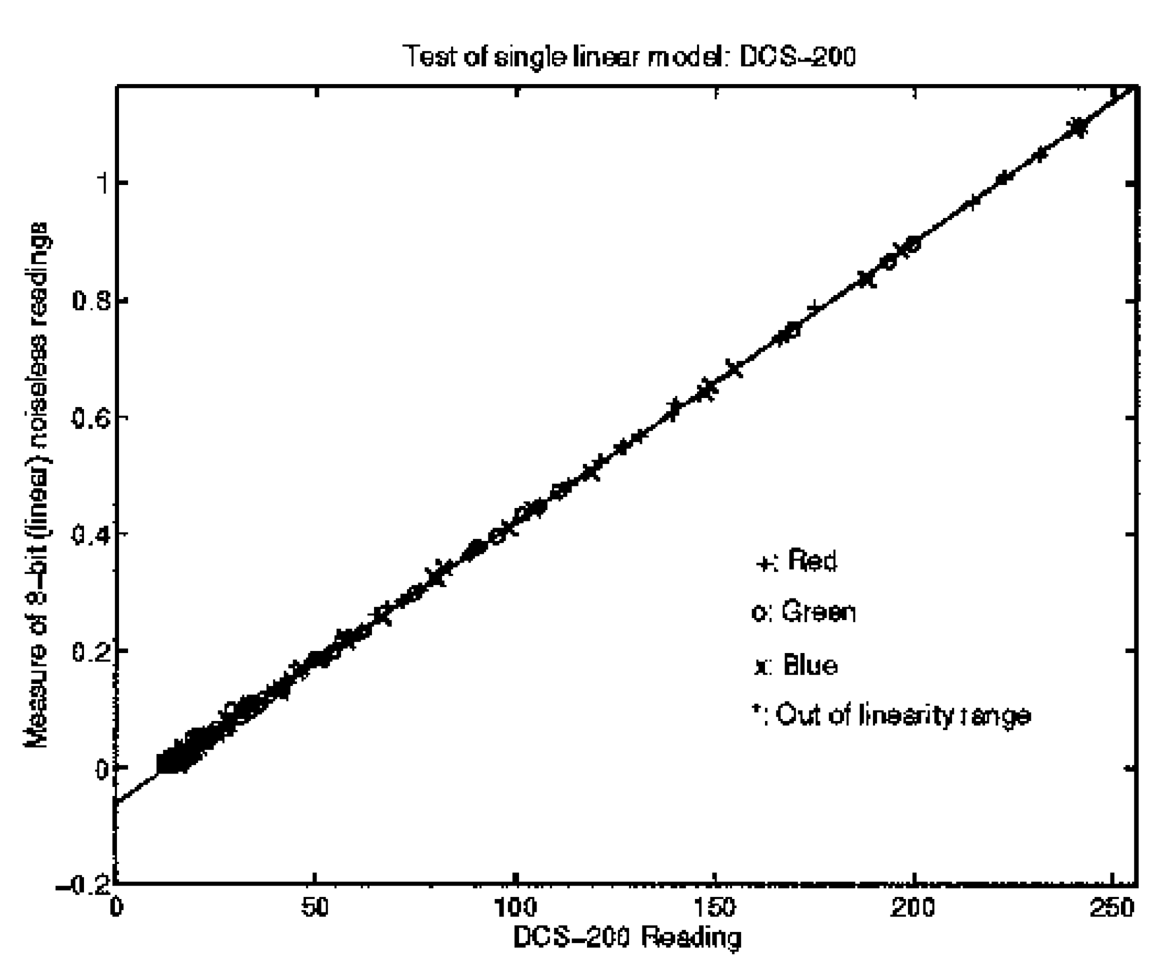

Figure 1: Linearity Map for DCS-200.

The fact that the data, once normalized, all fall along the same line indicates that the camera response is linear with both intensity and exposure at different wavelengths [3].

2.2 Camera response model for the Kodak DCS-420

The behavior of the Kodak DCS-420 can be described by a the *static non-linearity model.* For this model, the camera response for a pixel of the i^{th} sensor type pixel is given by

$$r_i \;=\; \mathcal{F}(e\int_{\lambda_l}^{\lambda_h} s_i(\lambda)i(\lambda)d\lambda \;+\; n_i) \qquad (1)$$

where $\mathcal{F}$ is a monotonically increasing non-linear function.

To examine whether the static non-linearity response model describes the performance of the DCS-420, we determined how well a single function $\mathcal{F}$ can describe its output across the conditions we measured.

Figure 2 shows that a camera response model can explain camera behavior as a function of both intensity and exposure. As in Figure 1 the normalized intensity response is plotted as a function of the camera DAC output [3].

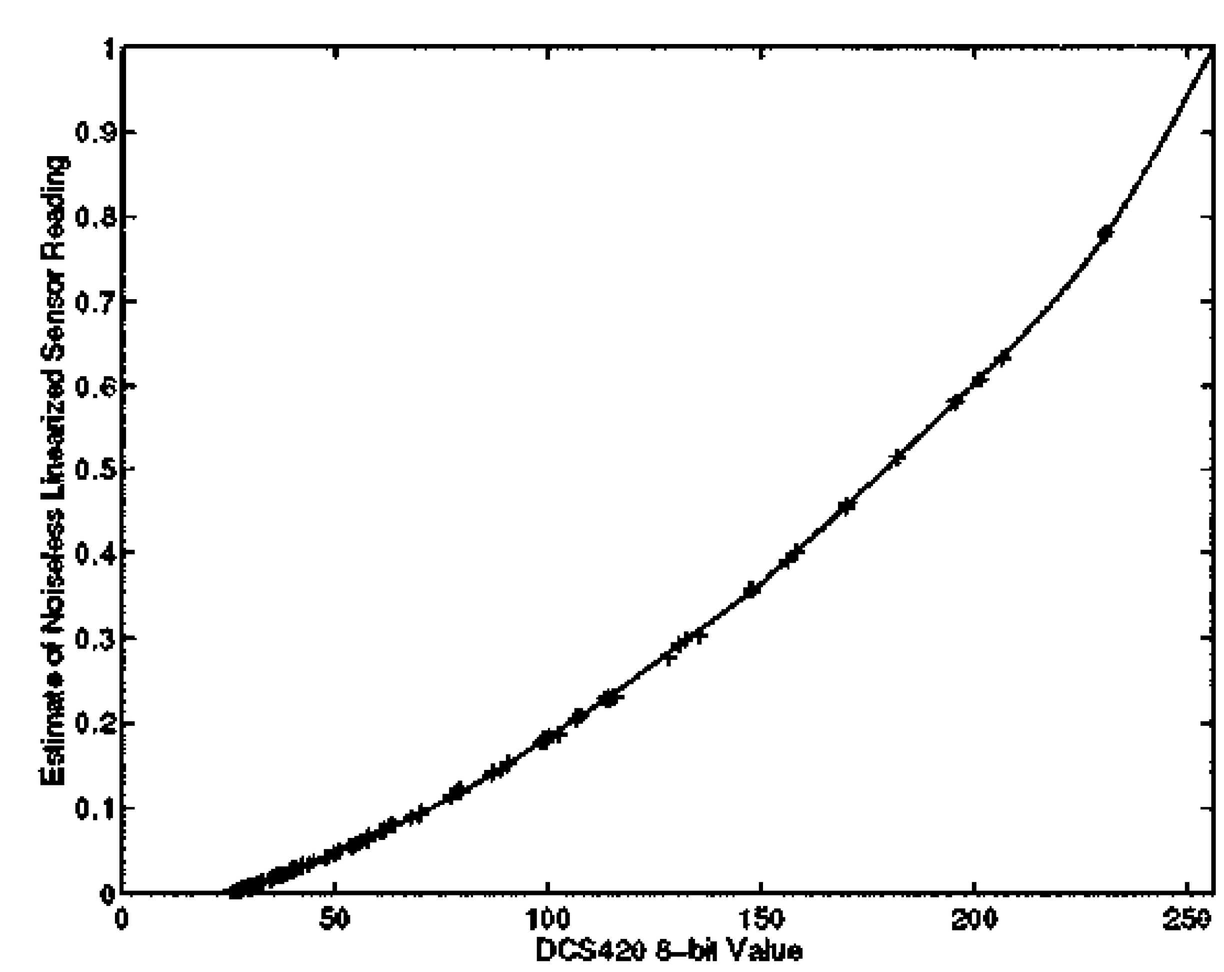

Figure 2: Calibration Curve - DCS-420.

3 Spectral calibration

In this section, we describe the spectral calibration of the Kodak DCS-200 and Kodak DCS-420 digital cameras. The calibration procedure is based on the response models we developed and tested for these cameras in the previous section [3]. First, we describe how we collected the spectral calibration data. Then we describe a simple method for estimating the camera sensor spectral response functions. Finally, we determine if our estimates of the DCS-200 can predict the camera responses for images of the Macbeth ColorChecker Chart (MCC).

3.1 Methods

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 [3]. 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 $\times$ 64 pixels for the DCS-420 and 30 $\times$ 25 pixels for the DCS-200).

For the DCS-200, we excluded measurements outside of the camera's linear operating range. We corrected the measured responses for the camera dark current by subtracting our estimate of its mean values. For the DCS-420, we used a look-up table based on Figure 2 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.

3.2 Simple Estimate

To perform calculations, we write a sampled version of equation (1) that describes the entire calibration data set. Let $\mathbf{r}$, $\mathbf{g}$, and $\mathbf{b}$ be vectors representing the R, G, B readings to a series of narrowband lights. The vectors $\mathbf{r}$, $\mathbf{g}$, and $\mathbf{b}$ 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,

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

where $\mathbf{n}$ 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 $\mathbf{g}$ and $\mathbf{b}$.

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 narrowband. This fact may be used to approximate equation (2) by

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

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} narrow-band 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 [4]. The function $\mathcal{F}$ is the identity for the DCS-200 and $\bar{n} = 13.6$ from the experiments detailed in [3]. For the DCS-420, the quantity $\mathcal{F}^{-1}(\mathbf{r}_i) - \bar{n}$ may be obtained from the calibration curve provided in Figure 2.

Figure 3 shows plots of the simple estimates obtained for the DCS-200 and Figure 4 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. The expression

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

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 calibration curve in Figure 2 was used. We compared the predicted RGB values to the measurements. Figure 5 shows plots of the measured R, G and B values against the values indicated by expression (4) for the DCS-200, while Figure 6 shows the same for the DCS-420.

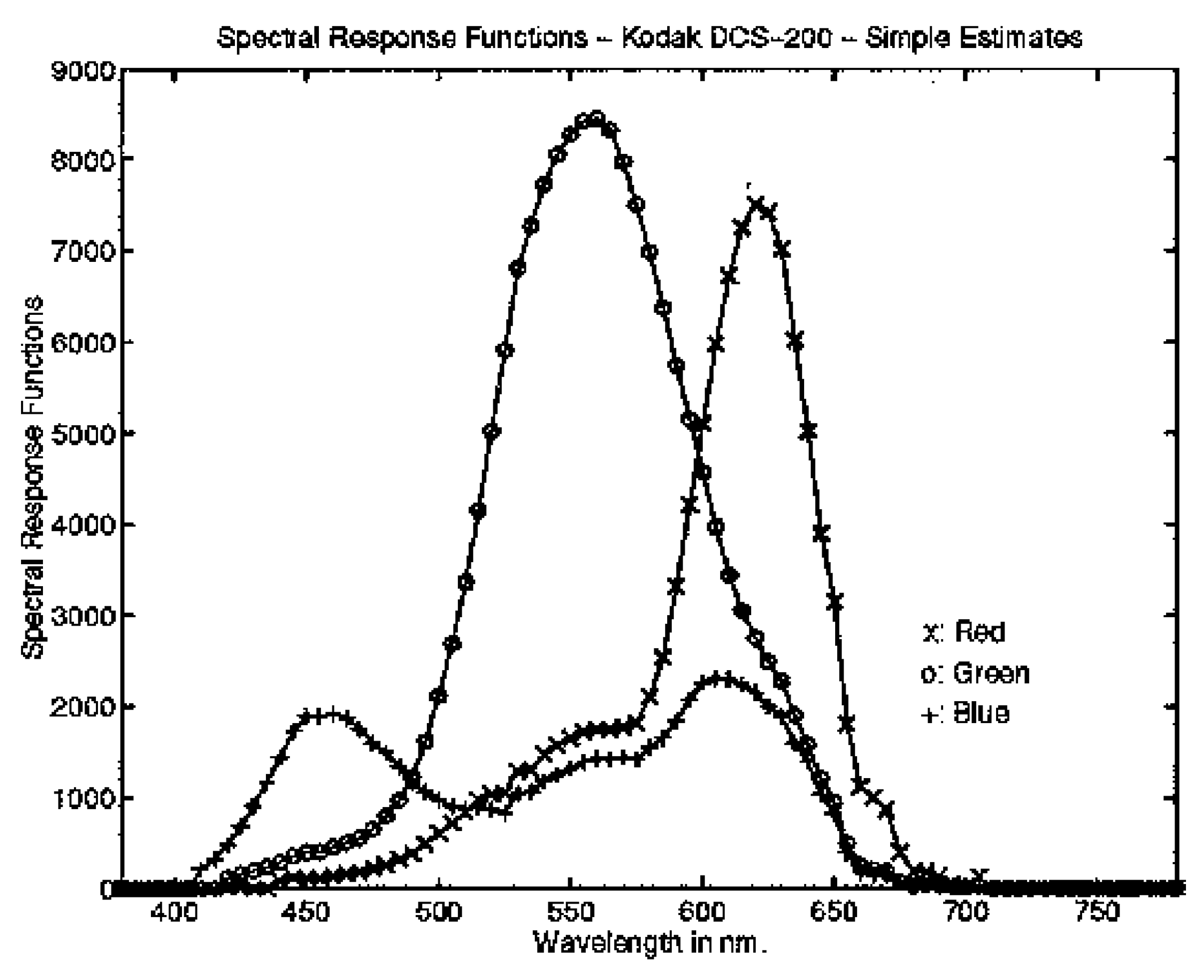

Figure 3: Spectral Response Functions of the Kodak DCS-200 - Simple Estimate.

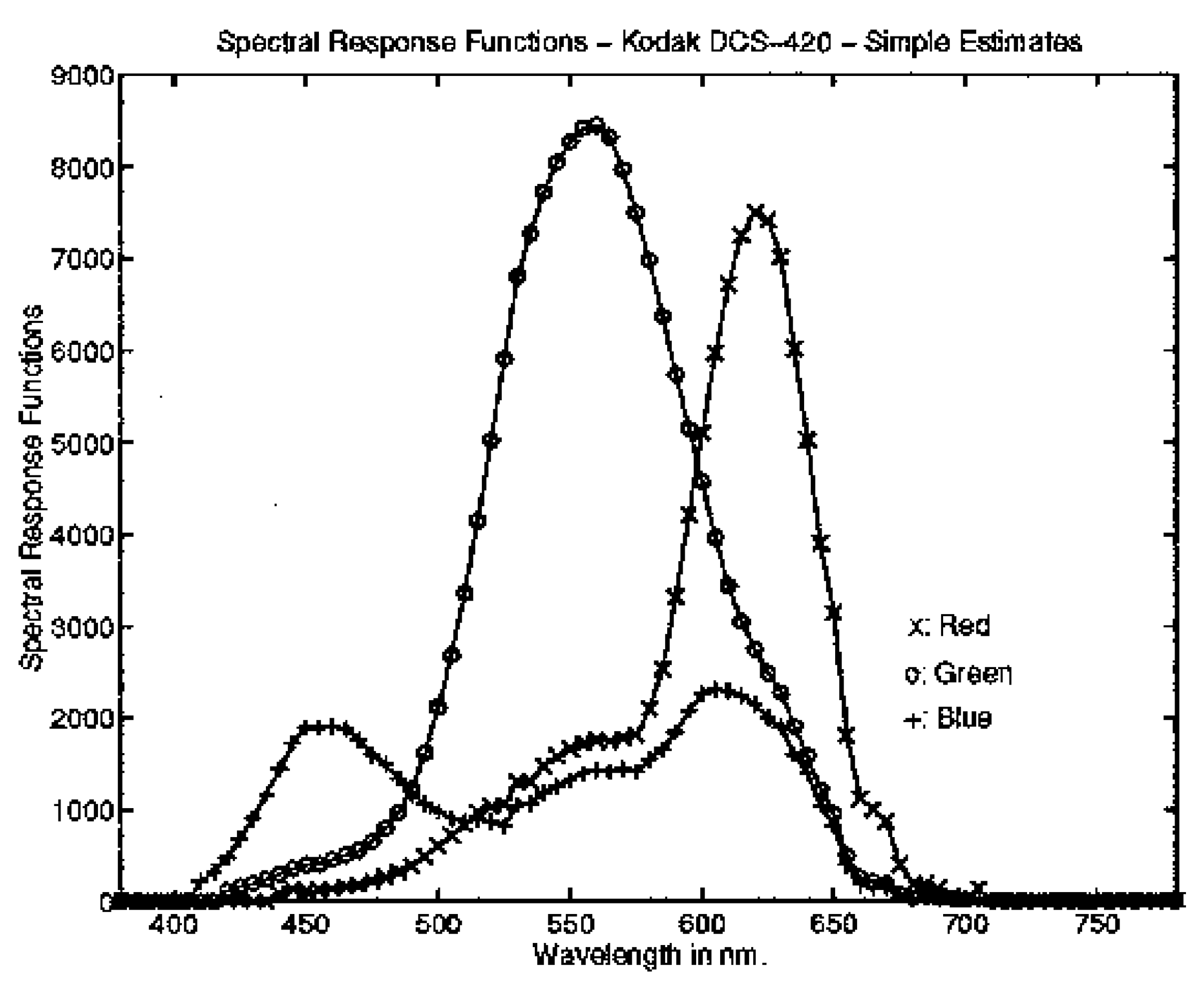

Figure 4: Spectral Response Functions of the Kodak DCS-420 - Simple Estimate.

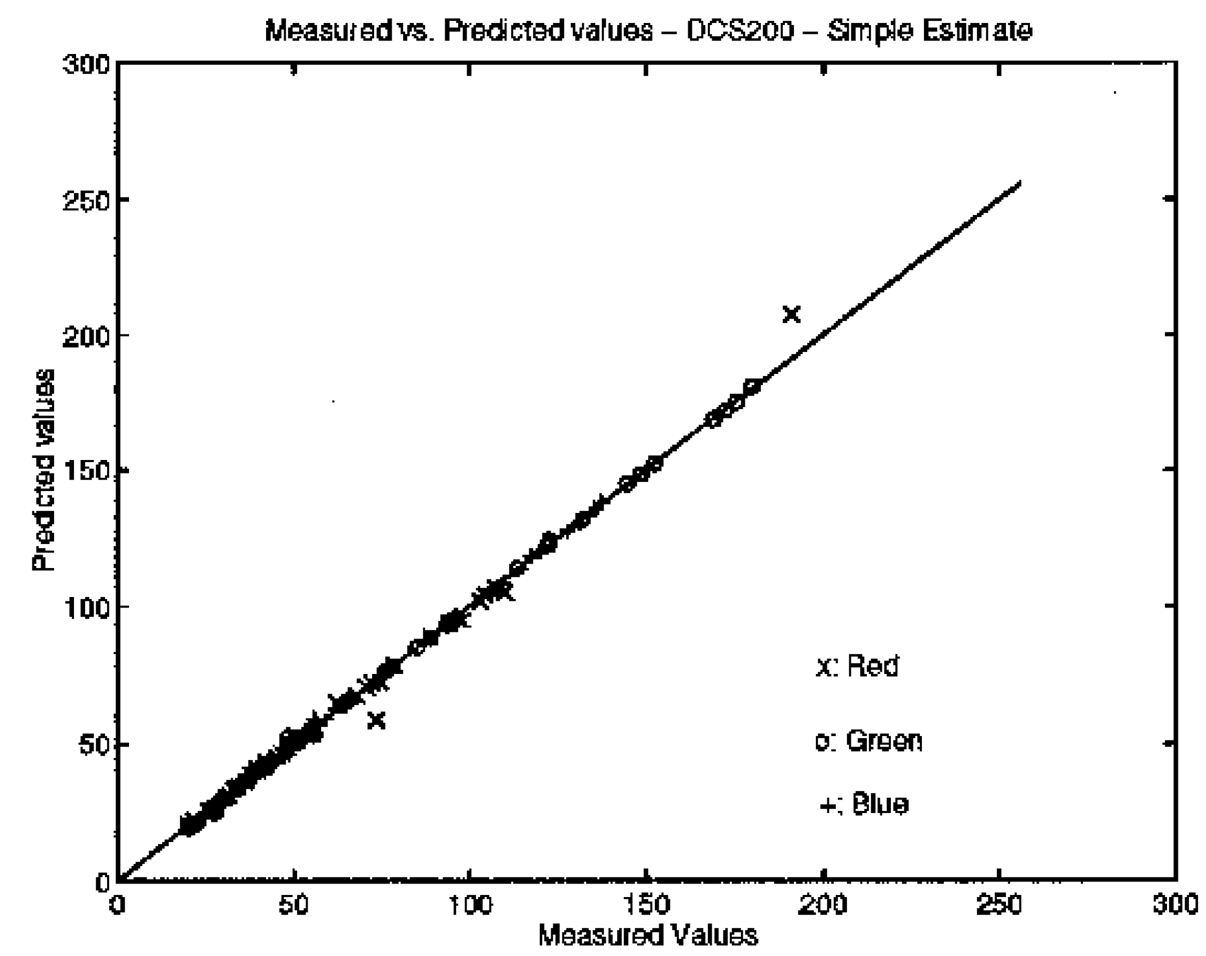

Figure 5: Measured vs. Predicted Values Kodak DCS-200 - Simple Estimate.

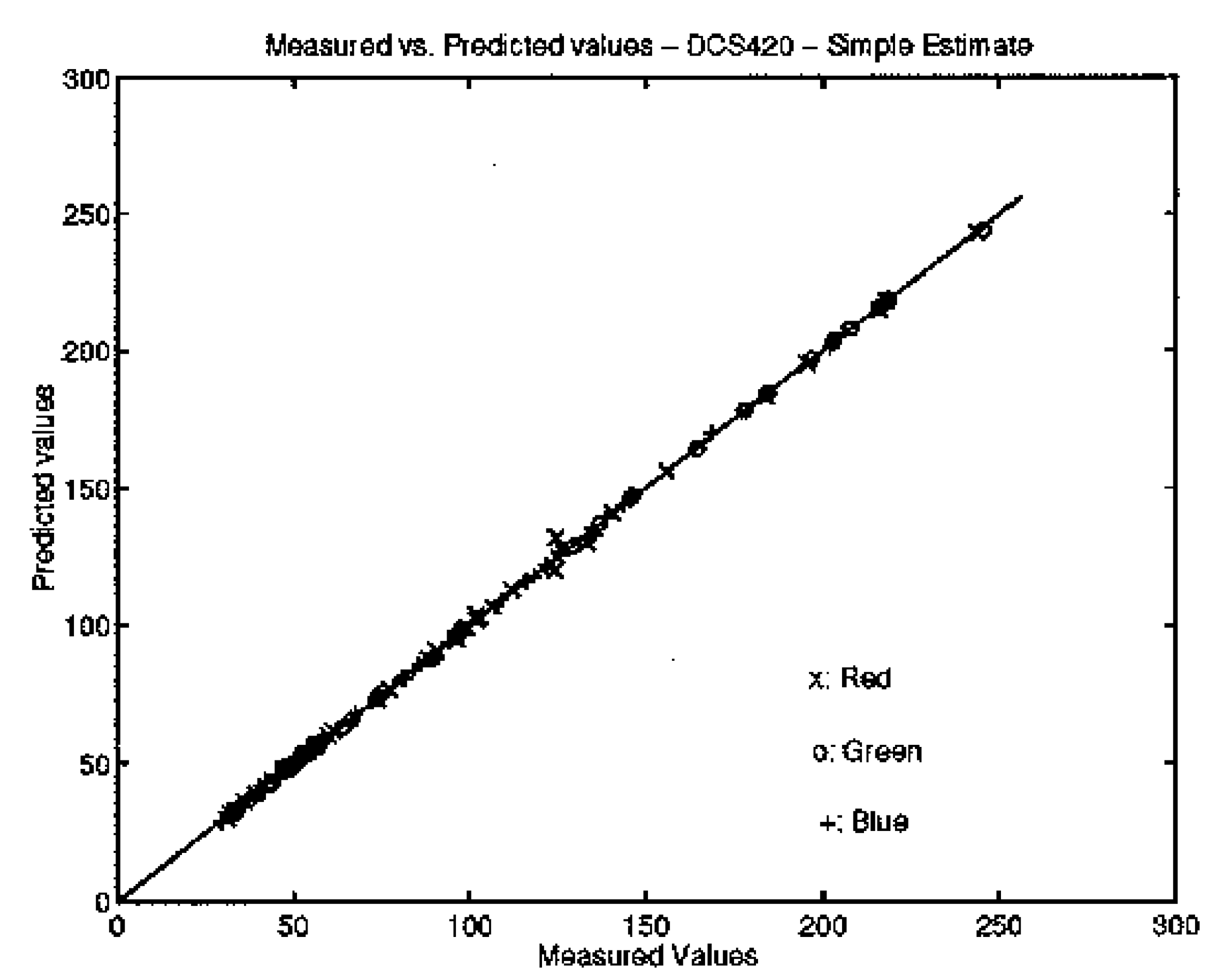

Figure 6: Measured vs. Predicted Values Kodak DCS-420 - Simple Estimate.

In this study, we used narrow-band light sources and investigated a wide range of estimates. We found that a simple estimation method did as well as more complicated Wiener estimation methods [5].

In contrast to our previous attempts to estimate the spectral sensitivities of the Kodak digital camera [4], the error for both the simple and Wiener estimates are low and close to the rms value predicted by the noise statistics for both cameras. This suggests that sensor estimation methods are data-limited. In other words, the estimates depend more on the information available in the data than on apriori assumptions about the spectral sensitivity functions. 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 [4].

Non-linear estimation methods like Projections Onto Convex Sets (POCS) [6] 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.

4 Verification of Estimates

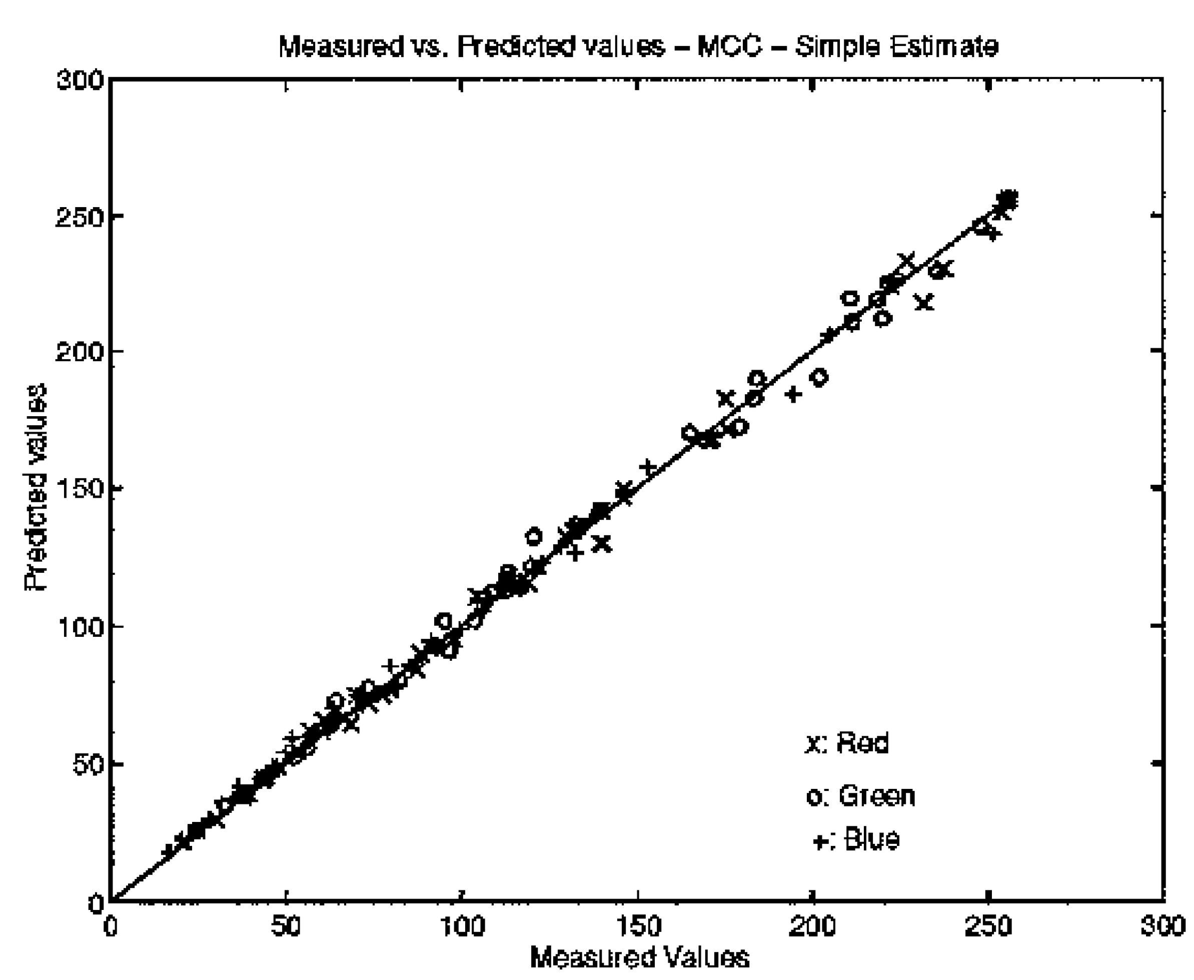

Figure 7: Measured vs. Predicted Values for MCC - Kodak DCS-200 - Simple Estimate.

For the DCS-200, we tested the spectral sensitivity estimates by collecting two images of the MCC under a tungsten illuminant. 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 20×20 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. Figure 7 shows the predicted vs. measured values for the simple estimate.

5 Conclusions

We investigated whether a linear response model describes the behavior of two CCD-based digital cameras. The Kodak DCS-200 is well-described by a linear response model, while the Kodak DCS-420 (when used with the 8-bit driver software) is not. It is possible, however, to use calibration data to correct the DCS-420 output to obtain linearized values.

We used the linearized camera responses to narrowband light sources to estimate 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. The Kodak DCS-200 estimates were also used to predict the RGB values of the MCC, which did not form part of the calibration data set. The prediction error for the MCC was also low for both simple and Wiener estimates. 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.

The performance of the estimates is good enough for us to use them with confidence in a digital camera simulator [7].

References

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