Multi-spectral Image Acquisition and Spectral Reconstruction using a Trichromatic Digital Camera System associated with absorption filters PART Va Spectral reconstruction in reflectance space: Target I

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Abstract

This part describes the simulation performed to reconstruct the spectral reflectance of Macbeth ColorChecker, in reflectance space using several combinations of filters and trichromatic signals. It also reports the colorimetric and spectral accuracy of the reconstructions, as well as the metameric index.

I) Linear method using simulated digital counts (IBM DCS)

The idea of the linear method using simulated digital counts is summarized in the flowchart of Figure 1. At first, a camera model is built considering the spectral sensitivities of the digital camera, spectral power distribution of the illuminant, and the spectral transmittance of the filters used in the digitization. The spectral reflectances **R** of the samples are measured and principal component analysis is performed to calculate the eigenvectors Φ. The eigenvalues **a** corresponding to the spectral reflectances **R** is calculated. The camera model is used to obtain simulated digital counts from spectral reflectances **R**. A transformation matrix **A** from digital counts to eigenvalues **a** is computed.

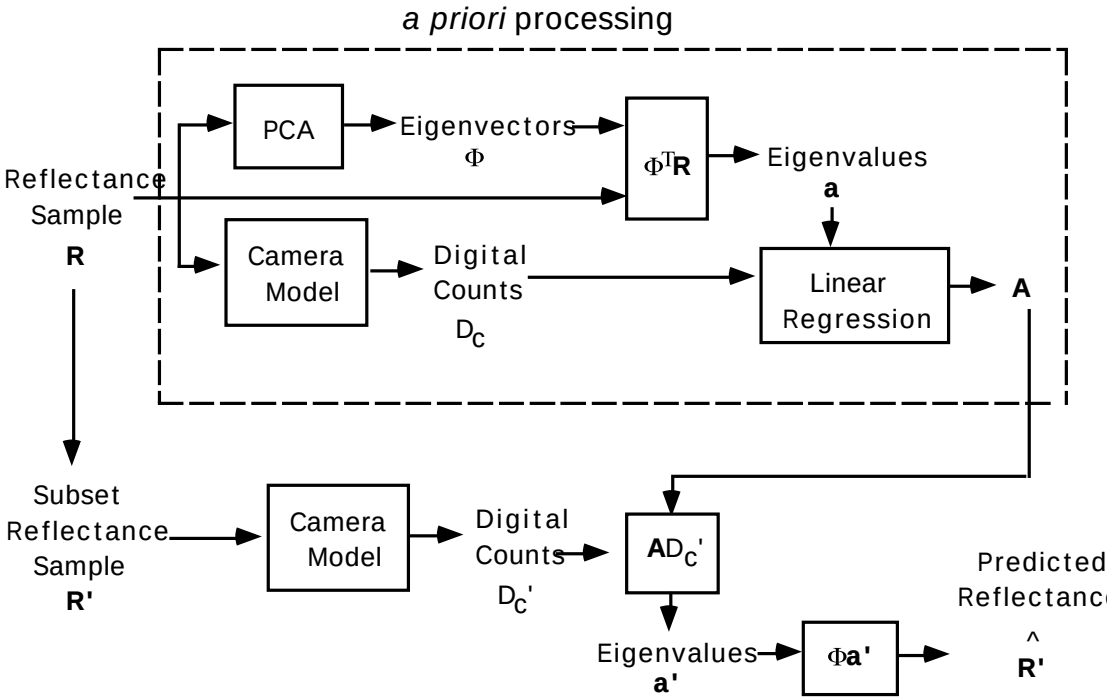


Figure 1. Flowchart of the linear method

The digital counts Dc' of a subset **R'** of the spectral reflectances is simulated using the camera model. The transformation matrix **A**, calculated *a priori,* is used to predict the eigenvalues **a'** corresponding to the digital counts Dc'. Finally, the spectral reflectance $\hat{\mathbf{R}}$**'** is predicted using the eigenvalues **a'** and eigenvectors Φ.

Important consideration on normalization

At first, all the simulations were performed without normalizing the digital counts between zero and one. The maximum values of the digital counts have order of 10^3 while the coefficients of the eigenvectors that are predicted from the digital counts are less than a unity. The inaccuracy of the inverse transformation matrix that gives the coefficients of the eigenvectors in function of the digital counts produced poor results using linear method. Therefore, every digital counts were normalized dividing by 4,095.

Target I: Macbeth ColorChecker

The Macbeth ColorChecker was imaged for various combinations of R, G, and B channels without filters and with filters (Kodak Wratten filters number 38 and 66 plus Didymium filter). The results of the spectral reconstruction for 6 channels are summarized in Table I to VI.

6 eigenvectors and channels (R, G, B without filter and with Wratten filter number 38)

Table I. Spectral reconstruction using 6 eigenvectors; 6 signals: R, G, B without filter and R, G, B with Wratten absorption filter number 38.

Patch	ΔE^*_{94}	**reflectance rms error factor**	**Metameric Index**
Dark skin	0.30	0.007	0.14
Light skin	0.04	0.012	0.04
Blue sky	0.45	0.016	0.16
Foliage	0.54	0.015	0.33
Blue flower	0.12	0.016	0.11
Bluish green	0.26	0.018	0.10
Orange	0.57	0.025	0.31
Purplish red	0.08	0.015	0.30
Moderate red	0.36	0.023	0.21
Purple	**1.07**	**0.053**	**1.13**
Yellow green	0.28	0.016	0.33
Orange yellow	0.65	0.020	0.61
Blue	**0.80**	**0.035**	**1.77**
Green	**0.63**	0.011	0.36
Red	**0.73**	0.025	**0.68**
Yellow	0.05	0.015	0.14
Magenta	0.46	0.024	0.34
Cyan	**0.86**	0.026	0.33
White	0.23	0.016	0.04
Neutral 8	0.41	0.017	0.10
Neutral 6.5	0.42	0.019	0.16
Neutral 5	0.35	0.013	0.13
Neutral 3.5	0.32	0.006	0.10
Black	0.21	0.002	0.08
Average	**0.42**	**0.021**	**0.33**
Std Dev	0.27	0.010	0.39
Max	1.07	0.053	1.77
Min	0.04	0.002	0.04

The spectral reconstruction for every combination of filters produced quite accurate colorimetric results. Since the colorimetric accuracy graph for all the patches do not produce perceptible difference in a* x b* plot for different combination of filters, they were omitted in this report. As an example, Figure 2 shows the colorimetric accuracy for the spectral reconstruction using 6 eigenvectors, 6 channels (R, G, B without filter and with Wratten absorption filter number 38). Instead of representing the a* x b* plot, the results were presented in the form of ΔE^*_{94} histograms. The spectral and colorimetric accuracy are shown in Figures 3 to 14.

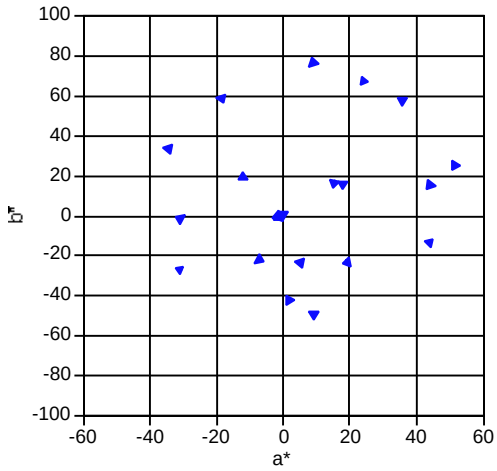


Figure 2. Colorimetric accuracy using 6 eigenvectors; 6 signals: R, G, B without filter and with Wratten absorption filter number 38; (original -> reproduction).

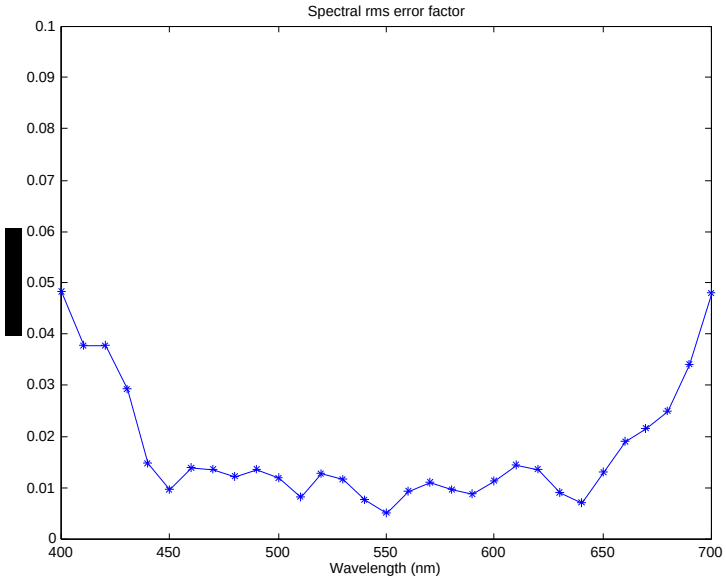


Figure 3. Spectral rms error for spectral reconstruction using 6 eigenvectors; 6 signals: R, G, B without filter and with Wratten absorption filter number 38.

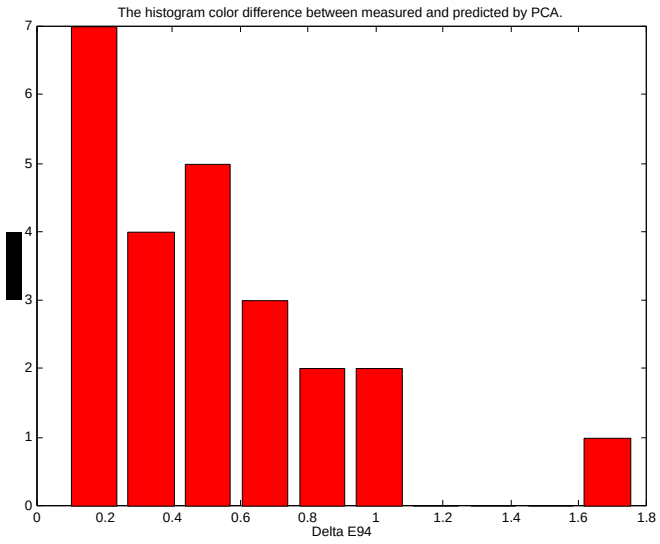


Figure 4. ΔE^*_{94} histogram for spectral reconstruction using 6 eigenvectors; 6 signals: R, G, B without filter and with Wratten absorption filter number 38.

6 eigenvectors; 6 channels (R, G, B without filter and with Wratten filter number 66)

Table II. Spectral reconstruction using 6 eigenvectors; 6 signals : R, G, B without filter and with Wratten absorption filter number 66.

Patch	ΔE^*_{94}	**reflectance rms error factor**	**Metameric Index**
Dark skin	0.16	0.006	0.08
Light skin	0.12	0.012	0.01
Blue sky	0.23	0.012	0.08
Foliage	**0.65**	0.018	**0.47**
Blue flower	0.08	0.014	0.03
Bluish green	0.15	0.022	0.06
Orange	0.25	0.023	0.18
Purplish red	0.32	0.016	0.04
Moderate red	0.34	0.020	0.20
Purple	**0.60**	**0.038**	**0.69**
Yellow green	0.12	0.015	0.23
Orange yellow	0.22	0.020	0.42
Blue	**0.79**	**0.028**	**0.89**
Green	0.26	0.011	0.28
Red	0.03	0.016	0.09
Yellow	0.07	0.014	0.07
Magenta	0.25	0.015	0.12
Cyan	0.23	0.018	0.33
White	0.22	0.016	0.06
Neutral 8	0.21	0.015	0.05
Neutral 6.5	0.19	0.016	0.06
Neutral 5	0.15	0.011	0.05

Neutral 3.5	0.13	0.006	0.04
Black	0.08	0.002	0.03
Average	**0.24**	**0.018**	**0.19**
Std Dev	0.19	0.007	0.23
Max	0.79	0.038	0.89
Min	0.03	0.002	0.01

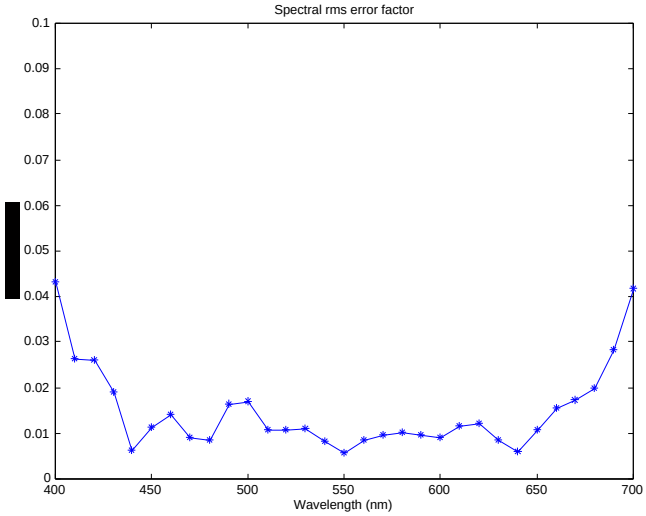


Figure 5. Spectral rms error for spectral reconstruction using 6 eigevenvectors; 6 signals: R, G, B without filter and R, G, B with Wratten absorption filter number 66.

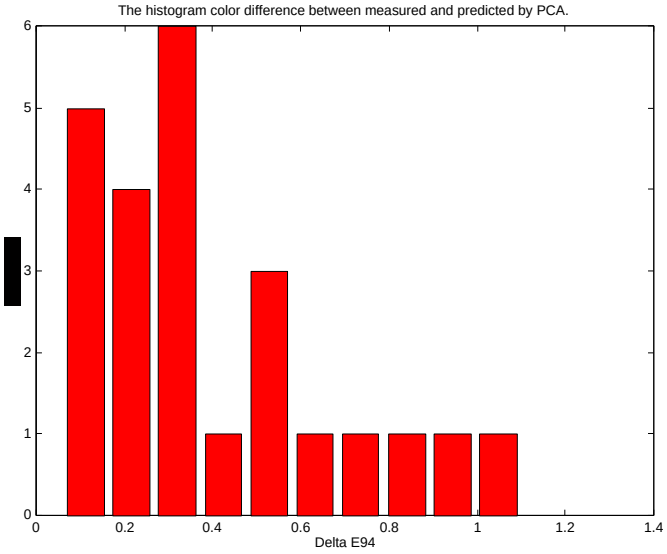


Figure 6. ΔE^*_{94} histogram for spectral reconstruction using 6 eigenvectors; 6 signals: R, G, B without filter and R, G, B with Wratten absorption filter number 66.

6 eigenvectors; 6 channels (R, G, B without filter and with didymium filter)

Table III. Spectral reconstruction using 6 signals: R, G, B without filter and with didymium filter.

Patch	ΔE^*_{94}	reflectance rms error factor	Metameric Index
Dark skin	0.27	0.005	0.09
Light skin	0.31	0.015	0.45
Blue sky	0.46	0.013	0.05
Foliage	**1.23**	**0.019**	**1.73**
Blue flower	0.31	0.020	0.58
Bluish green	0.57	0.021	0.91
Orange	0.54	0.017	0.25
Purplish red	0.87	0.027	1.72
Moderate red	**1.14**	**0.035**	**1.91**
Purple	**1.34**	**0.044**	**2.25**
Yellow green	0.53	0.024	1.20
Orange yellow	0.52	0.025	0.29
Blue	**1.35**	**0.027**	**3.34**
Green	0.42	0.010	0.30
Red	0.18	0.013	0.02
Yellow	0.28	0.017	0.63
Magenta	0.75	0.024	0.98
Cyan	0.95	0.019	1.31
White	0.09	0.020	0.16
Neutral 8	0.13	0.018	0.12
Neutral 6.5	0.07	0.014	0.08
Neutral 5	0.17	0.011	0.18
Neutral 3.5	0.12	0.006	0.04
Black	0.05	0.002	0.02
Average	**0.53**	**0.021**	**0.78**
Std Dev	0.42	0.009	0.88
Max	1.35	0.044	3.34
Min	0.05	0.002	0.02

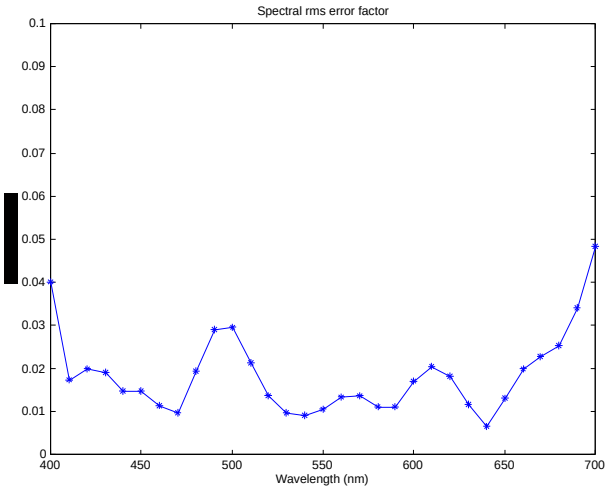


Figure 7. Spectral rms error for spectral reconstruction using 6 eigenvectors; 6 signals: R, G, B without filter and with didymium filter.

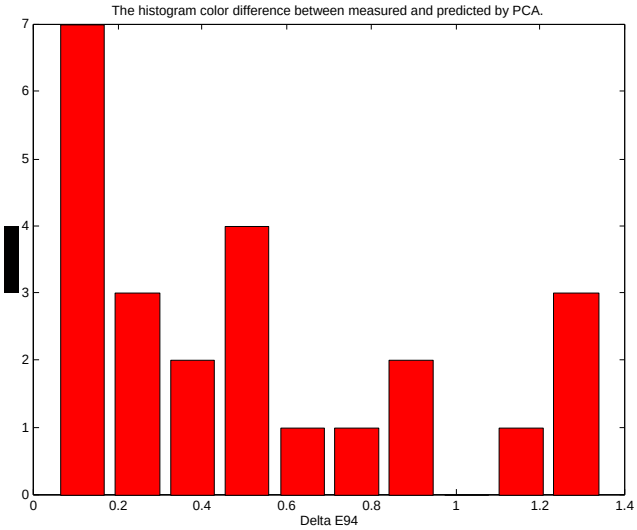


Figure 8. ΔE^*_{94} histogram for spectral reconstruction using 6 eigenvectors; 6 signals: R, G, B without filter and with didymium filter.

6 eigenvectors; 6 channels (R, G, B with Wratten absorption filter number 38 and with didymium filter)

Table IV. Spectral reconstruction using 6 eigenvectors; 6 signals: R, G, B with Wratten absorption filter number 38 and with didymium filter.

Patch	ΔE^*_{94}	**reflectance rms error factor**	**Metameric Index**
Dark skin	0.43	0.006	0.22

Light skin	0.18	0.015	0.28
Blue sky	0.57	0.014	0.24
Foliage	**1.03**	0.019	**1.33**
Blue flower	0.39	0.020	0.33
Bluish green	0.40	0.019	0.51
Orange	0.76	0.019	0.41
Purplish red	0.48	0.025	0.82
Moderate red	**0.89**	0.034	**0.87**
Purple	**1.77**	**0.051**	**1.77**
Yellow green	0.55	0.028	1.05
Orange yellow	0.65	0.022	0.79
Blue	0.49	0.020	0.96
Green	0.66	0.013	0.75
Red	0.26	0.013	0.33
Yellow	0.19	0.015	0.34
Magenta	0.94	0.030	0.80
Cyan	0.82	0.018	0.80
White	0.14	0.022	0.14
Neutral 8	0.23	0.019	0.10
Neutral 6.5	0.14	0.015	0.05
Neutral 5	0.25	0.011	0.11
Neutral 3.5	0.18	0.006	0.03
Black	0.08	0.002	0.01
Average	**0.52**	**0.021**	**0.54**
Std Dev	0.38	0.010	0.45
Max	1.77	0.051	1.77
Min	0.08	0.002	0.01

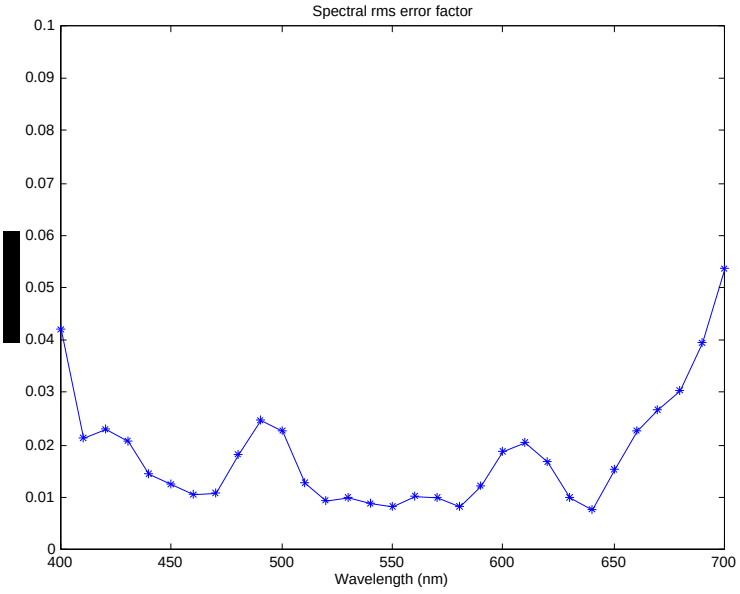


Figure 9. Spectral rms error for spectral reconstruction using 6 eigenvectors; 6 signals: R, G, B with Wratten absorption filter number 38 and with didymium filter.

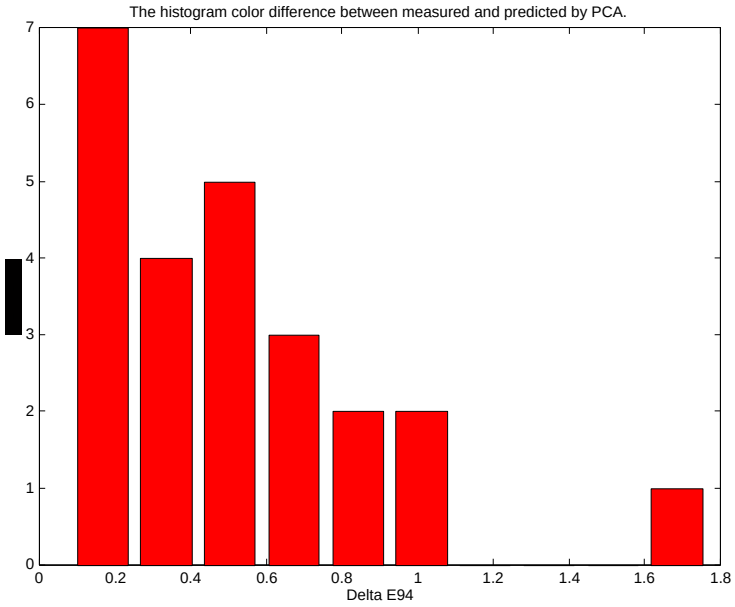


Figure 10. ΔE^*_{94} histogram for spectral reconstruction using 6 eigenvectors; 6 signals: R, G, B with Wratten absorption filter number 38 and with didymium filter.

6 eigenvectors; 6 channels (R, G, B with Wratten absorption filters number 38 and 66)

Table V. Spectral reconstruction using 6 eigenvectors; 6 signals: R, G, B with Wratten absorption filters number 38 and 66.

Patch	ΔE^*_{94}	reflectance rms error factor	Metameric Index
Dark skin	0.30	0.005	0.05
Light skin	0.09	0.013	0.02
Blue sky	0.45	0.017	0.06
Foliage	**1.50**	0.016	0.37
Blue flower	0.13	0.017	0.13
Bluish green	0.35	0.026	0.04
Orange	0.66	0.018	0.36
Purplish red	0.31	0.018	0.11
Moderate red	0.19	0.038	0.35
Purple	**1.75**	**0.038**	0.29
Yellow green	0.16	0.017	0.24
Orange yellow	0.35	0.034	0.04
Blue	**1.15**	**0.032**	**0.79**
Green	0.27	0.014	0.13
Red	0.09	0.017	0.35
Yellow	0.06	0.016	0.15
Magenta	0.24	0.022	0.33

Cyan	0.27	0.027	0.10
White	0.17	0.020	0.06
Neutral 8	0.13	0.023	0.05
Neutral 6.5	0.18	0.019	0.07
Neutral 5	0.10	0.014	0.07
Neutral 3.5	0.08	0.007	0.03
Black	0.06	0.002	0.02
Average	**0.38**	**0.022**	**0.18**
Std Dev	0.45	0.009	0.18
Max	1.75	0.038	0.79
Min	0.06	0.002	0.02

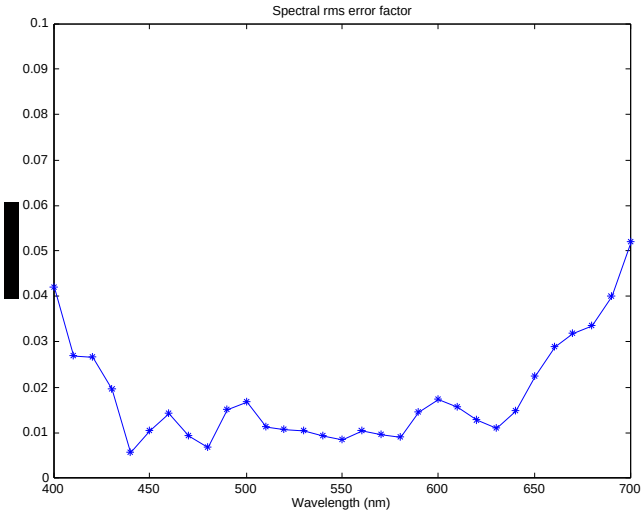


Figure 11. Spectral rms error for spectral reconstruction using 6 eigenvectors; 6 signals: R, G, B with Wratten absorption filters number 38 and number 66.

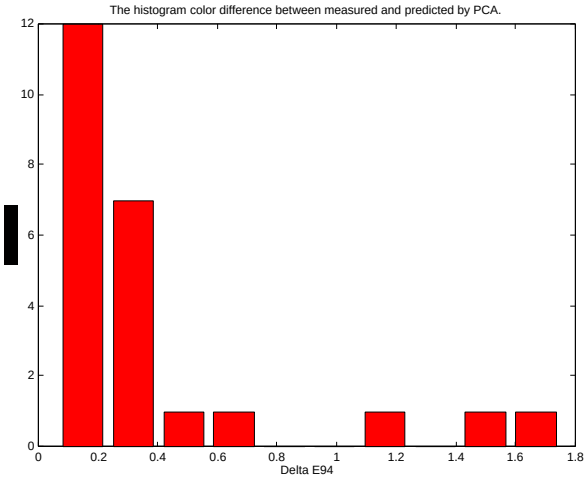


Figure 12. ΔE^*_{94} histogram for spectral reconstruction using 6 eigenvectors; 6 signals: R, G, B with Wratten absorption filters number 38 and 66.

6 eigenvectors; 6 channels (R, G, B with Wratten absorption filter number 66 and with didymium filter)

Table VI. Spectral reconstruction using 6 eigenvectors; 6 signals: R, G, B with Wratten absorption filter number 66 and with didymium filter).

Patch	ΔE^*_{94}	reflectance rms error factor	Metameric Index
Dark skin	0.29	0.005	0.10
Light skin	0.06	0.013	0.06
Blue sky	0.53	0.015	0.10
Foliage	**0.80**	0.018	0.62
Blue flower	0.30	0.016	0.15
Bluish green	0.31	0.024	0.05
Orange	0.53	0.018	0.25
Purplish red	0.33	0.017	0.41
Moderate red	**0.77**	**0.028**	**0.75**
Purple	**1.10**	**0.037**	0.33
Yellow green	0.23	0.016	0.34
Orange yellow	0.40	0.030	0.14
Blue	**0.97**	**0.027**	**1.94**
Green	0.31	0.013	0.20
Red	0.35	0.012	0.37
Yellow	0.14	0.014	0.28
Magenta	0.49	0.016	0.23
Cyan	0.67	0.022	0.59
White	0.13	0.017	0.14
Neutral 8	0.20	0.019	0.16
Neutral 6.5	0.12	0.017	0.14
Neutral 5	0.21	0.013	0.15
Neutral 3.5	0.17	0.006	0.10
Black	0.08	0.002	0.07
Average	**0.39**	**0.019**	**0.32**
Std Dev	0.28	0.008	0.39
Max	1.10	0.037	1.94
Min	0.06	0.002	0.05

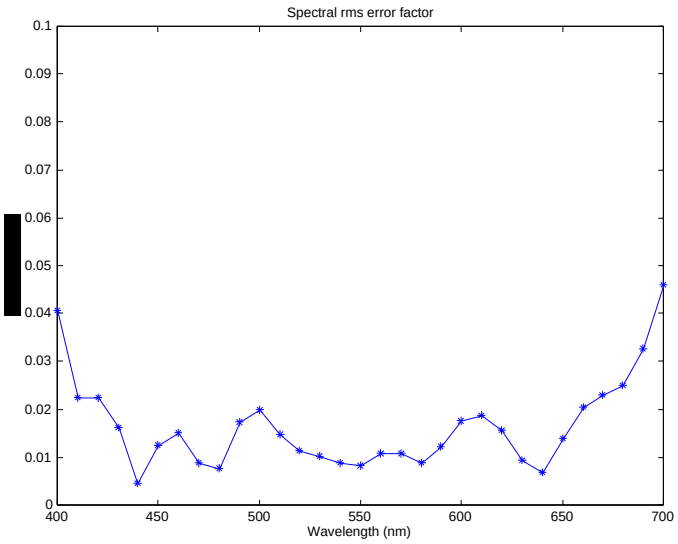


Figure 13. Spectral rms error for spectral reconstruction using 6 eigenvectors; 6 signals: R, G, B with Wratten absorption filter number 66 and with didymium filter.

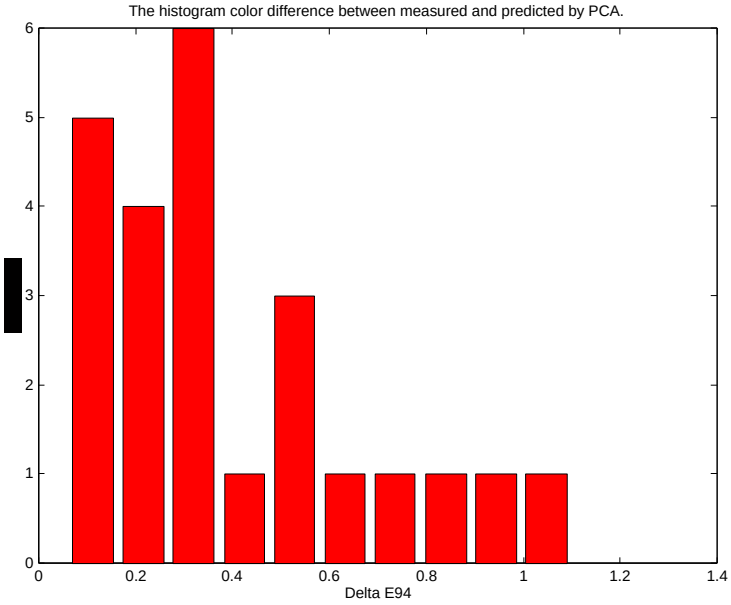


Figure 14. ΔE^*_{94} histogram for spectral reconstruction using 6 eigenvectors; 6 signals: R, G, B with Wratten absorption filter number 66 and with didymium filter.

From Figures 2 to 14 and Tables I to VI, it is possible to see that although all the tested filter combinations presented an acceptable range of colorimetric and spectral performances, the best overall averaged colorimetric and spectral results are obtained for

the spectral reconstruction using 6 eigenvectors and 6 signals from R, G, B without filter and R, G, B with very light green Wratten absorption filter number 66.
On the other hand, the combination of R, G, B signals with light blue Wratten absorption filter number 38 and with didymium filter produced the worst results. Looking at the tables it is possible to observe that the purple patch presented the biggest color difference and spectral rms error factor. A spectral mismatch of purple patch reproduced using R, G, B signals without filter and with light blue filter is presented in Figure 15. The use of R, G, B signals without filter combined with the R, G, B signals with very light green filter produced better results in the spectral reconstruction of purple patch as shown in Figure 16.

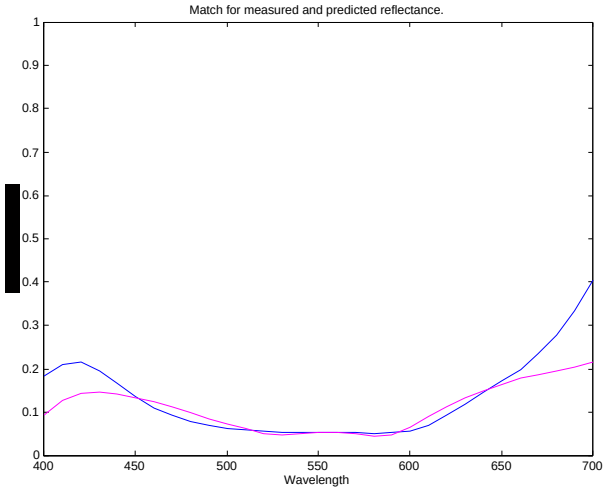


Figure 15. Comparison of the measured and estimated spectral reflectance of the purple patch of the Macbeth ColorChecker using 6 eigenvectors and 6 signals: R, G, B without filter and with light blue filter (Wratten absorption filter number 38).

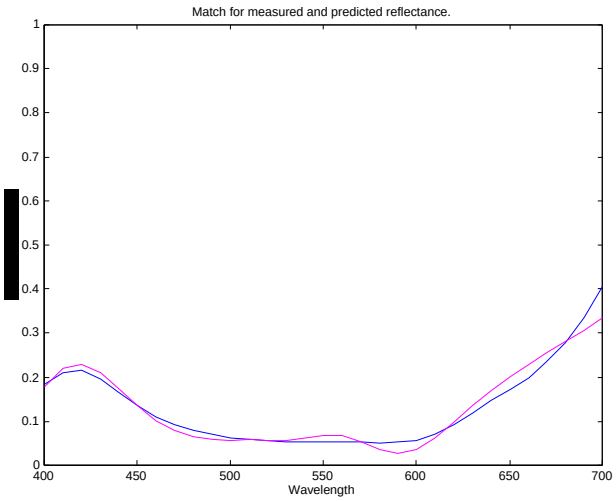


Figure 16. Comparison of the measured and estimated spectral reflectance of the purple patch of the Macbeth ColorChecker using 6 eigenvectors and 6 signals: R, G, B without filter and with very light green filter (Wratten absorption filter number 66).
Blue and foliage patches of the Macbeth ColorChecker, whose spectral reconstruction are shown, respectively, in Figures 17 and 18, also presented spectral mismatches.

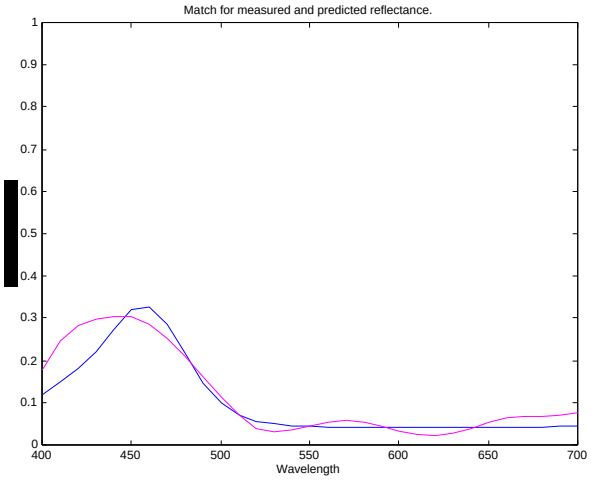


Figure 17. Comparison of the measured and estimated spectral reflectance of the blue patch of the Macbeth ColorChecker using 6 eigenvectors and 6 signals: R, G, B without filter and with light blue filter (Wratten absorption filter number 38).

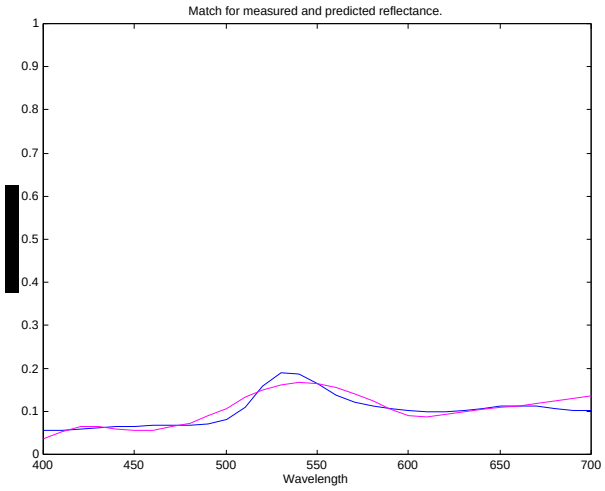


Figure 18. Comparison of the measured and estimated spectral reflectance of the foliage patch of the Macbeth ColorChecker using 6 eigenvectors and 6 signals: R, G, B without filter and with light blue filter (Wratten absorption filter number 38).

From the results above, it is reasonable to assume that the low digital counts of the images of bluish objects (purple, blue patches of Macbeth ColorChecker) due to the spectral characteristics of the imaging system (illuminant), are the reason for the mismatches in these colors.

In the case of the foliage patch of Macbeth ColorChecker, it is possible that 6 eigenvectors are not sufficient to reconstruct this kind of spectral curve in reflectance space.

It also possible to observe that the use of didymium filter worsened the spectral reconstruction of moderate red patch of Macbeth ColorChecker. I guess that the attenuation valley of the didymium spectral transmittance used to separate green and red signals is also attenuating too much the signals used to reconstruct the reflectance of this patch.

Effect of changing the number of eigenvectors to 9 channels and 9 eigenvectors

9 eigenvectors, 9 channels (R, G, B with without filter, with Wratten absorption filters number 38 and 66)

Table VII. Spectral reconstruction using 9 eigenvectors; 9 signals: R, G, B without filter, with Wratten absorption filters number 38 and 66.

Patch	ΔE^*_{94}	**reflectance rms error factor**	**Metameric Index**
Dark skin	0.21	0.005	0.07

Light skin	0.10	0.009	0.05
Blue sky	0.09	0.012	0.06
Foliage	0.24	0.011	0.15
Blue flower	0.07	0.011	0.04
Bluish green	0.08	0.007	0.03
Orange	0.43	0.012	0.20
Purplish red	0.10	0.008	0.06
Moderate red	0.06	0.009	0.07
Purple	0.15	0.004	0.04
Yellow green	0.19	0.009	0.10
Orange yellow	0.05	0.007	0.04
Blue	0.24	0.009	0.15
Green	0.43	0.009	0.12
Red	0.31	0.009	0.10
Yellow	0.11	0.008	0.09
Magenta	0.22	0.011	0.08
Cyan	0.11	0.007	0.04
White	0.22	0.019	0.05
Neutral 8	0.10	0.007	0.03
Neutral 6.5	0.09	0.011	0.03
Neutral 5	0.06	0.008	0.03
Neutral 3.5	0.05	0.004	0.02
Black	0.04	0.002	0.02
Average	**0.16**	**0.009**	**0.07**
Std Dev	0.11	0.003	0.05
Max	0.43	0.019	0.20
Min	0.04	0.002	0.02

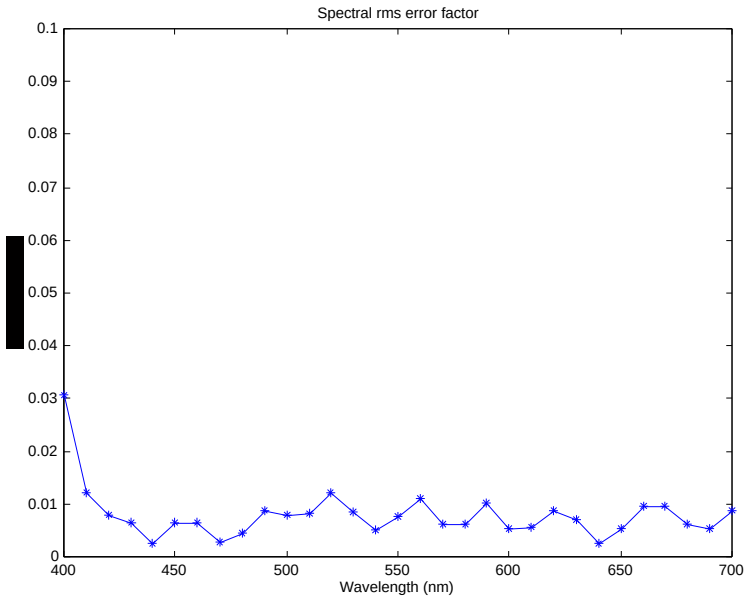


Figure 19. Spectral rms error for spectral reconstruction using 9 signals: R, G, B without filter, with Wratten absorption filters number 38 and 66.

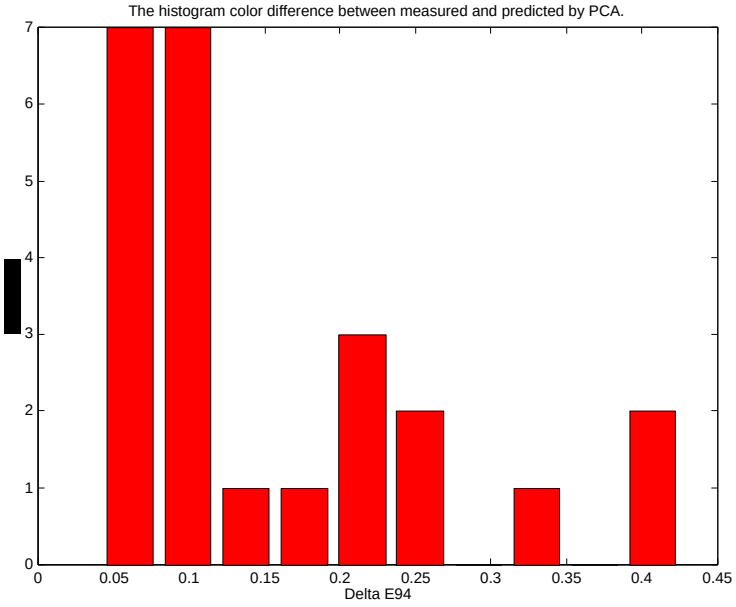


Figure 20. ΔE^*_{94} histogram for spectral reconstruction using 9 signals: R, G, B without filter, with Wratten absorption filters number 38 and 66.

9 eigenvectors, 9 channels (R, G, B with didymium filter, with Wratten absorption filters number 38 and 66)

Table VIII. Spectral reconstruction using 9 signals: R, G, B with didymium filter, with Wratten absorption filters number 38 and 66.

Patch	ΔE^*_{94}	**reflectance rms error factor**	**Metameric Index**
Dark skin	0.16	0.004	0.05
Light skin	0.07	0.008	0.04
Blue sky	0.77	0.012	0.13
Foliage	0.48	0.010	0.09
Blue flower	0.31	0.011	0.14
Bluish green	0.06	0.006	0.03
Orange	0.33	0.013	0.17
Purplish red	0.08	0.008	0.04
Moderate red	0.19	0.009	0.03
Purple	0.51	0.004	0.10
Yellow green	0.20	0.009	0.10
Orange yellow	0.26	0.006	0.06
Blue	0.21	0.009	0.13
Green	0.51	0.010	0.11
Red	1.05	0.009	0.17
Yellow	0.26	0.008	0.12
Magenta	0.26	0.012	0.06
Cyan	0.14	0.007	0.10
White	0.13	0.018	0.01
Neutral 8	0.46	0.008	0.07
Neutral 6.5	0.53	0.011	0.08
Neutral 5	0.39	0.008	0.07
Neutral 3.5	0.34	0.004	0.05
Black	0.26	0.002	0.04
Average	0.33	0.009	0.08
Std Dev	0.23	0.003	0.04
Max	1.05	0.012	0.17
Min	0.06	0.002	0.01

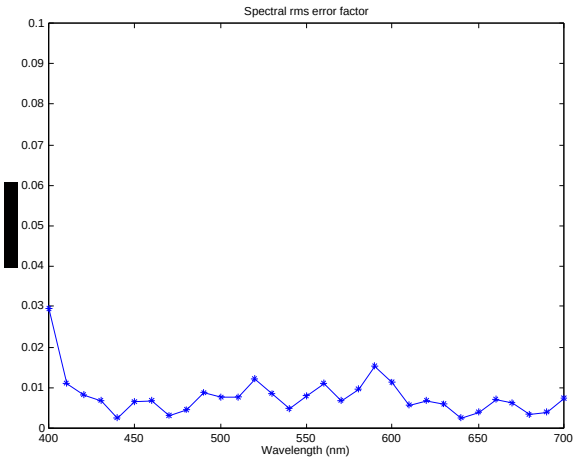


Figure 21. Spectral rms error for spectral reconstruction using 9 signals: R, G, B with didymium filter, with Wratten absorption filters number 38 and 66.

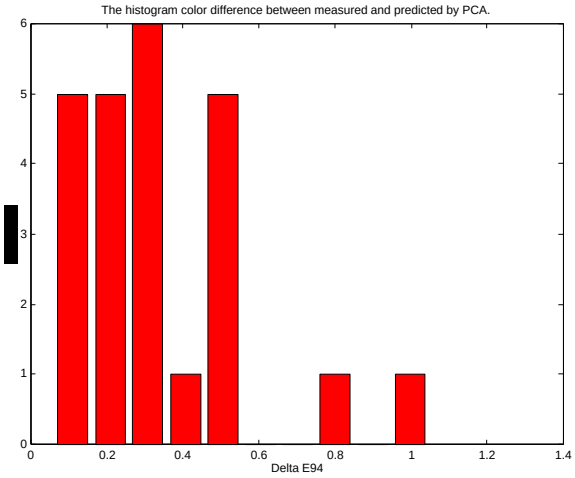


Figure 22. ΔE^*_{94} histogram for spectral reconstruction using 9 signals: R, G, B with didymium filter, with Wratten absorption filters number 38 and 66.

<u>9 eigenvectors, 9 channels (R, G, B with without filter, with didymium filter and Wratten absorption filter number 38)</u>

Table IX. Spectral reconstruction using 9 signals: R, G, B without filter, with didymium filter, and with Wratten absorption filter number 38.

Patch	ΔE^*_{94}	**reflectance rms error factor**	**Metameric Index**
Dark skin	0.24	0.005	0.07
Light skin	0.13	0.009	0.06
Blue sky	0.24	0.014	0.06
Foliage	0.45	0.014	0.13
Blue flower	0.11	0.012	0.05
Bluish green	0.10	0.010	0.04

Orange	0.39	0.012	0.19
Purplish red	0.13	0.014	0.07
Moderate red	0.14	0.013	0.08
Purple	0.25	0.027	0.06
Yellow green	0.20	0.011	0.12
Orange yellow	0.04	0.004	0.04
Blue	0.31	0.009	0.15
Green	0.51	0.011	0.10
Red	0.07	0.007	0.02
Yellow	0.10	0.009	0.10
Magenta	0.26	0.016	0.09
Cyan	0.12	0.009	0.08
White	0.22	0.020	0.05
Neutral 8	0.08	0.008	0.03
Neutral 6.5	0.11	0.011	0.05
Neutral 5	0.14	0.009	0.04
Neutral 3.5	0.13	0.005	0.04
Black	0.08	0.002	0.03
Average	**0.19**	**0.012**	**0.07**
Std Dev	0.12	0.005	0.04
Max	0.51	0.027	0.19
Min	0.04	0.002	0.02

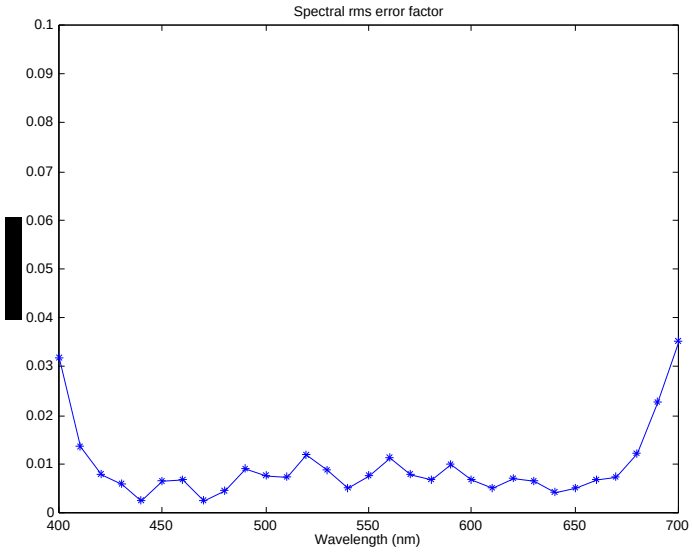


Figure 23. Spectral rms error for spectral reconstruction using 9 signals: R, G, B without filter, with didymium filter, and with Wratten absorption filter number 38.

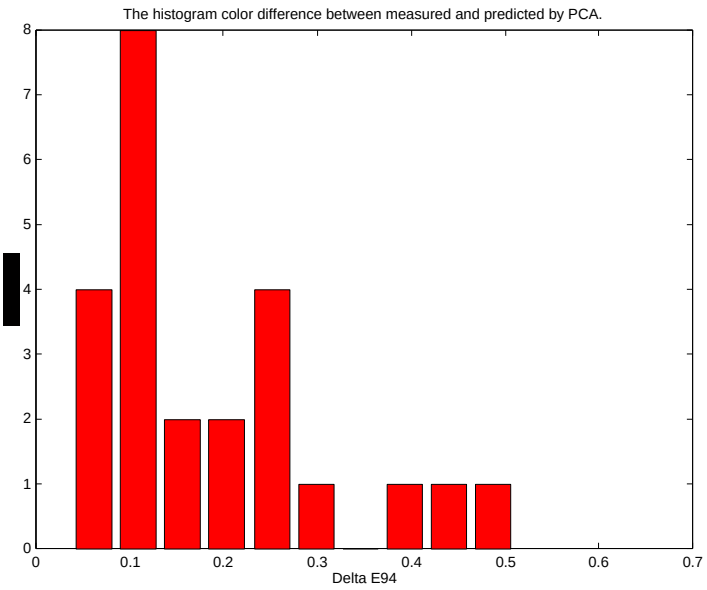


Figure 24. ΔE^*_{94} histogram for spectral reconstruction using 9 signals: R, G, B without filter, with didymium filter, and with Wratten absorption filter number 38.

9 eigenvectors, 9 channels (R, G, B with without filter, with didymium filter and Wratten absorption filter number 66)

Table X. Spectral reconstruction using 9 signals: R, G, B without filter, with didymium filter, and with Wratten absorption filter number 66.

Patch	ΔE^*_{94}	**reflectance rms error factor**	**Metameric Index**
Dark skin	0.27	0.005	0.08
Light skin	0.12	0.009	0.05
Blue sky	0.14	0.011	0.06
Foliage	0.28	0.011	0.18
Blue flower	0.12	0.011	0.07
Bluish green	0.06	0.008	0.09
Orange	0.40	0.012	0.20
Purplish red	0.06	0.013	0.27
Moderate red	0.10	0.022	0.28
Purple	0.41	0.019	0.60
Yellow green	0.15	0.011	0.13
Orange yellow	0.03	0.004	0.04
Blue	0.19	0.009	0.22
Green	0.53	0.010	0.14
Red	0.14	0.010	0.15
Yellow	0.09	0.008	0.07

Magenta	0.35	0.013	0.10
Cyan	0.10	0.008	0.16
White	0.21	0.020	0.01
Neutral 8	0.08	0.010	0.06
Neutral 6.5	0.04	0.012	0.04
Neutral 5	0.02	0.009	0.04
Neutral 3.5	0.03	0.005	0.05
Black	0.01	0.002	0.02
Average	**0.16**	**0.011**	**0.13**
Std Dev	0.14	0.005	0.12
Max	0.53	0.022	0.60
Min	0.01	0.002	0.01

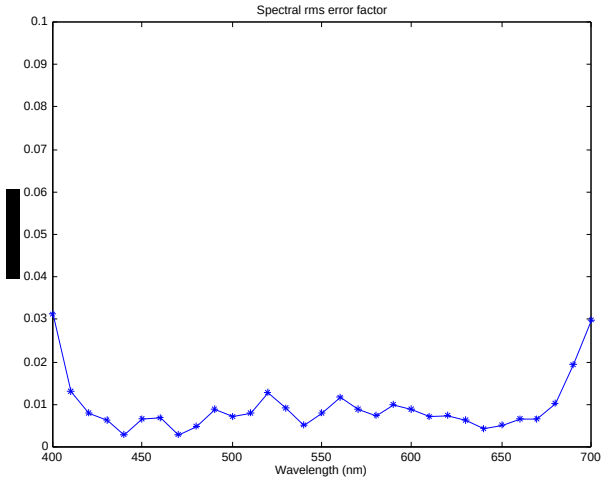


Figure 25. Spectral rms error for spectral reconstruction using 9 signals: R, G, B without filter, with didymium filter, and with Wratten absorption filter number 66.

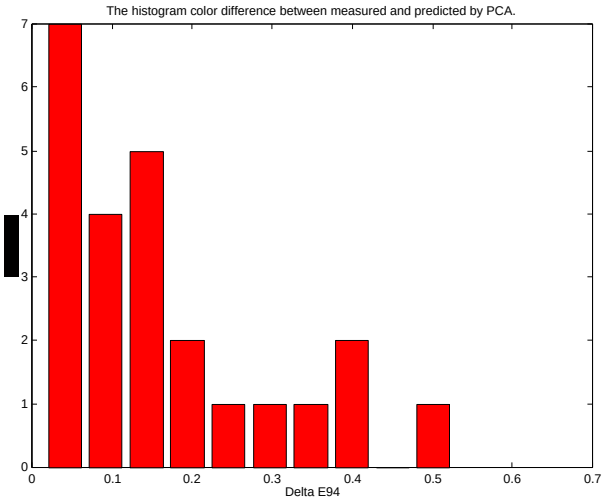


Figure 26. ΔE^*_{94} histogram for spectral reconstruction using 9 signals: R, G, B without filter, with didymium filter, and with Wratten absorption filter number 66.

From tables VII to X and figures 19 to 26, it is possible to observe that all filter combinations for spectral reconstruction with 9 eigenvectors and 9 signals presented very good colorimetric and spectral accuracy. The spectral reconstruction using 3 signals without filter, 3 signals with very light green and 3 signals with light blue filters presented the best overall performance. The substitution of 3 signals without filter by 3 signals of the didymium filtering worsened the spectral reconstruction of red channel.

The comparison of the measured spectral reflectance and the reconstructed reflectance of the purple patch of the Macbeth ColorChecker using 9 eigenvectors and 9 signals is shown in figure 26.

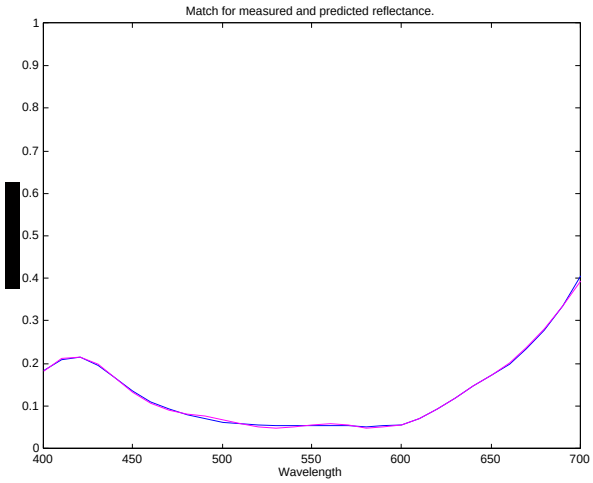


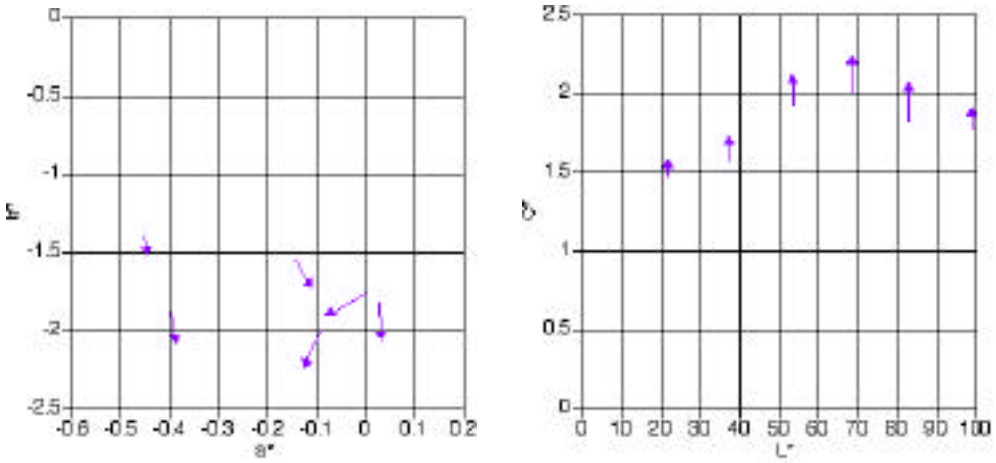
Figure 27. Comparison of the measured and estimated spectral reflectance of the purple patch of the Macbeth ColorChecker using 9 eigenvectors and 9 signals: R, G, B without filter, with Wratten absorption filters number 38 and 66.

From the observations above it is possible to conclude that 9 signals is needed in reflectance space to reconstruct the spectral reflectances of the Macbeth ColorChecker, in order to have $\mathbf{\Delta E^*_{94}}$ (D50, 2° observer) less than one and spectral reflectance rms error less than 2%.

GRAY BALANCE

6 eigenvectors; 6 channels (R, G, B without filter and with Wratten filter number 38)

The gray balance graphs is shown in Figure 28a and Figure 28b.

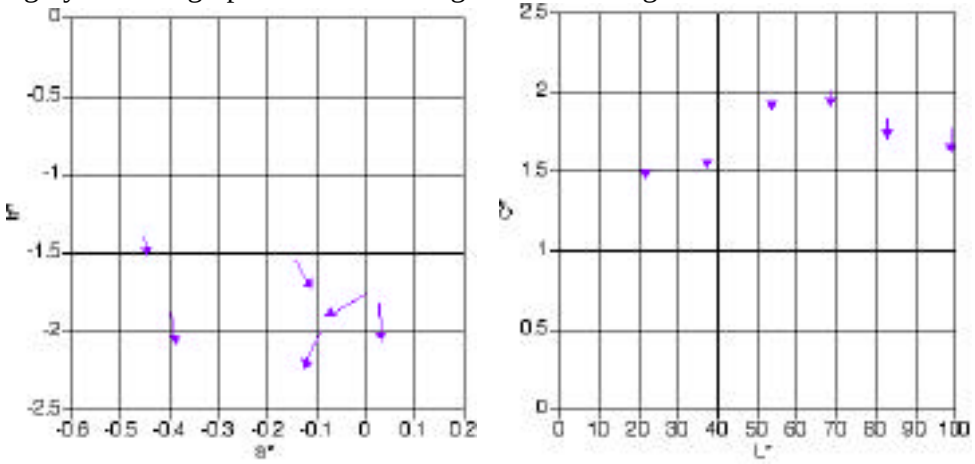


a) Gray a* x b* b) Gray L* x C*

Figure 28. Gray balance (original → reproduction) for 6 eigenvectors, 6 channel color reproduction (R, G, B without filter and with Wratten filter number 38).

9 eigenvectors, 9 channels (R, G, B with without filter, with Wratten absorption filters number 38 and 66)

The gray balance graphs is shown in Figure 29a and Figure 29b.



a) Gray a* x b* b) Gray L* x C*

Figure 29. Gray balance (original → reproduction) for 9 eigenvectors, 9 channel color reproduction (R, G, B with without filter, with Wratten absorption filters number 38 and 66).

II) <u>Linear method using measured digital counts</u>

This method uses basically the same idea of the linear method above, but instead of using simulated digital counts this method uses measured digital counts averaged from each patch as shown in Figure 29.

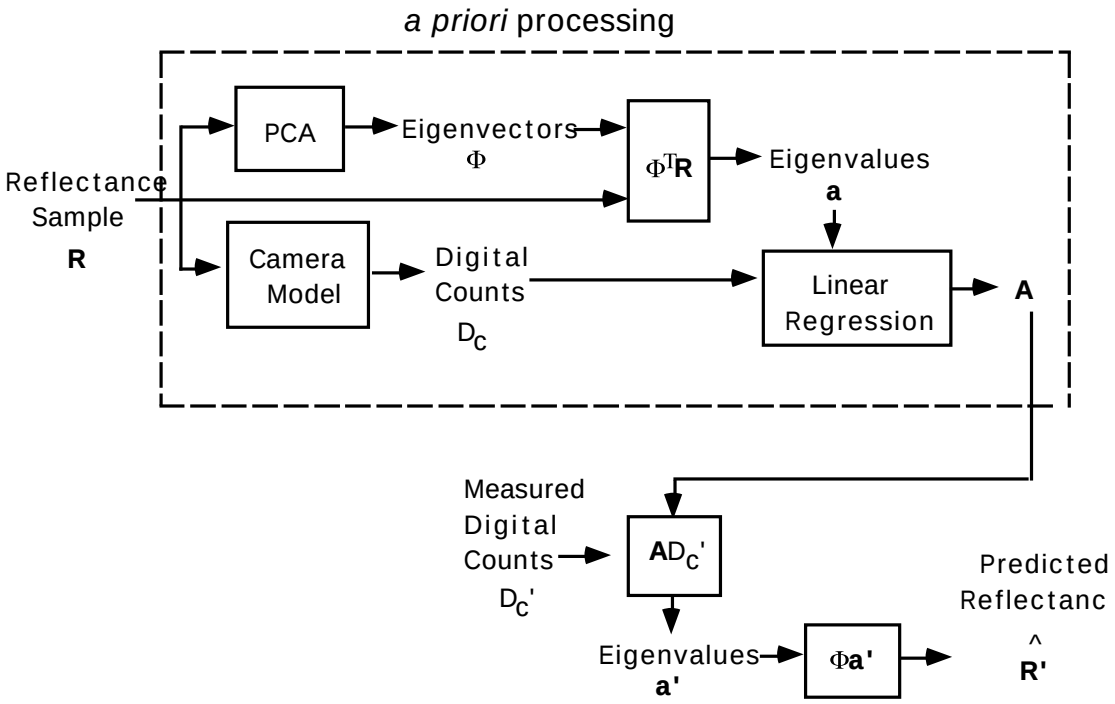


Figure 30. Flowchart of the linear method using measured digital counts

This method was applied for 6 eigenvectors and 6 channels (R, G, B without filter and with Wratten filter number 38). The results are summarized in Table XI and figures 31 and 33.

Table XI. Spectral reconstruction using 6 eigenvectors; 6 signals (R, G, B without filter and R, G, B with Wratten absorption filter number 66).

Patch	ΔE^*_{94}	**reflectance rms error factor**	**Metameric Index**
Dark skin	2.36	0.018	0.83
Light skin	0.76	0.013	0.21

Blue sky	1.37	0.019	1.05
Foliage	2.17	0.022	1.54
Blue flower	1.16	0.040	0.74
Bluish green	0.47	0.020	0.24
Orange	1.14	0.039	0.80
Purplish red	2.75	0.023	0.90
Moderate red	0.88	0.029	0.84
Purple	**5.19**	**0.074**	**1.52**
Yellow green	0.90	0.039	1.25
Orange yellow	1.50	0.025	0.46
Blue	**6.20**	0.044	1.05
Green	3.24	0.031	1.42
Red	2.59	0.039	1.43
Yellow	0.88	0.023	0.49
Magenta	1.22	0.033	0.83
Cyan	2.02	0.041	0.65
White	1.04	0.021	0.03
Neutral 8	0.98	0.020	0.19
Neutral 6.5	1.41	0.018	0.11
Neutral 5	1.92	0.017	0.63
Neutral 3.5	1.29	0.009	0.53
Black	5.72	0.016	1.19
Average	**2.05**	**0.031**	**0.79**
Std Dev	1.58		0.46
Max	6.20		1.54
Min	0.47		0.03

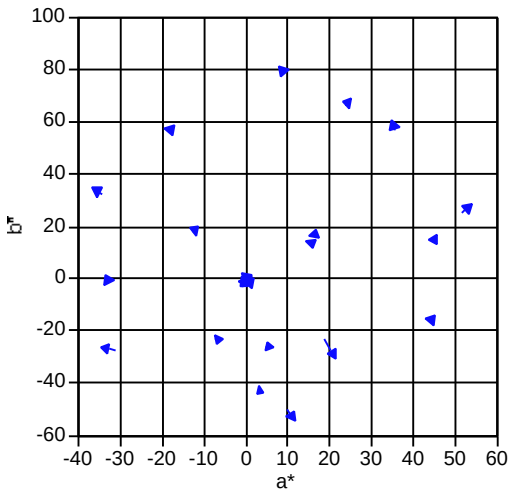


Figure 31. Colorimetric accuracy using 6 eigenvectors; 6 signals: R, G, B without filter and with Wratten absorption filter number 66; (original -> reproduction).

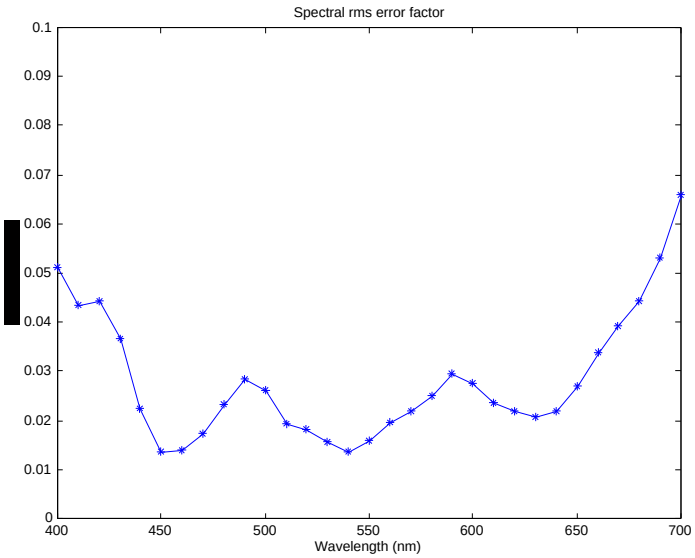


Figure 32. Spectral rms error for spectral reconstruction using 6 eigenvectors; 6 signals: R, G, B without filter and with Wratten absorption filter number 66.

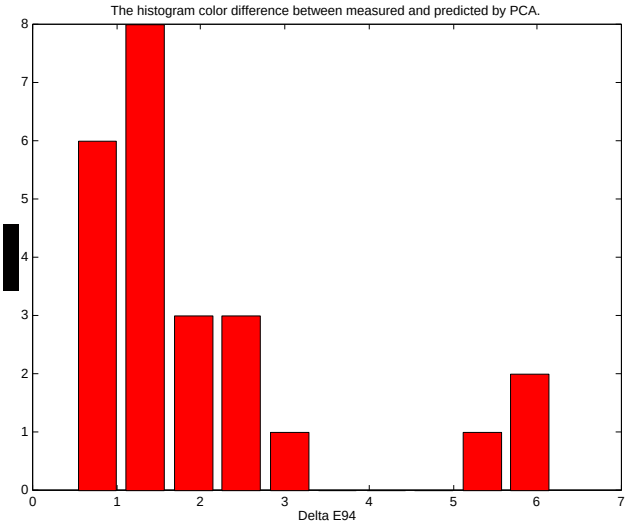


Figure 33. ΔE^*_{94} histogram for spectral reconstruction using 6 eigenvectors; 6 signals: R, G, B without filter and with Wratten absorption filter number 66.

III) Linear method using measured digital counts (Sony Digital Still Camera)

In order to test the performance of the method in Kubelka-Munk space for a common commercially available digital still camera, the Sony DKC-D5PRO camera was used. Table XII and figures 34 to 36 summarize the results.

Table XII. Spectral reconstruction using 6 eigenvectors; 6 signals : R, G, B without filter and with Wratten absorption filter number 38.

Patch	ΔE^*_{94}	**reflectance rms error factor**	**Metameric Index**
Dark skin	6.86	0.024	0.20
Light skin	2.19	0.028	0.96
Blue sky	2.64	0.027	0.86
Foliage	6.42	0.028	1.91
Blue flower	3.91	0.052	0.26
Bluish green	3.99	0.051	2.71
Orange	3.85	0.068	1.27
Purplish red	5.40	0.045	4.46
Moderate red	1.52	0.035	1.33
Purple	1.61	0.041	2.41
Yellow green	2.52	0.020	0.39
Orange yellow	1.96	0.040	1.70
Blue	9.26	0.076	8.03
Green	5.25	0.035	2.06
Red	3.37	0.044	2.86
Yellow	2.68	0.038	1.56
Magenta	1.58	0.048	1.12
Cyan	4.94	0.038	0.37
White	1.21	0.018	0.16
Neutral 8	0.29	0.017	0.18
Neutral 6.5	3.46	0.036	0.22
Neutral 5	1.12	0.014	0.25
Neutral 3.5	1.83	0.010	0.51
Black	3.36	0.006	0.43
Average	**3.38**	**0.035**	**1.51**
Std Dev	2.12	0.017	1.76
Max	9.26	0.076	8.03
Min	0.29	0.006	0.16

Figure 34 shows the colorimetric accuracy for the spectral reconstruction using 6 eigenvectors, 6 channels (R, G, B without filter and with Wratten absorption filter number 38).

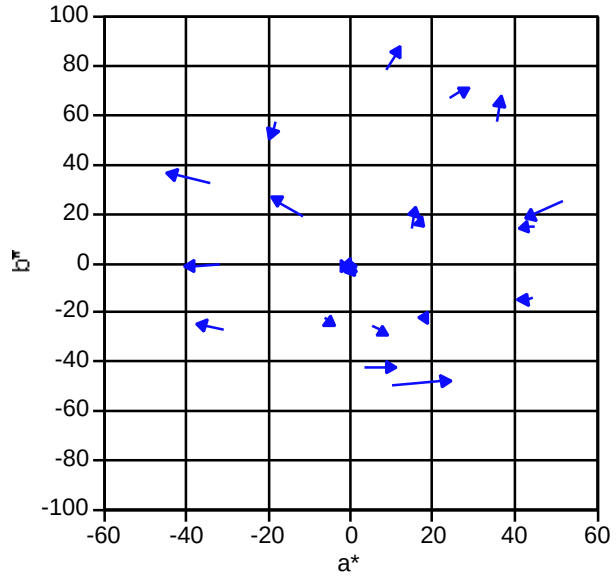


Figure 34 Colorimetric accuracy using 6 eigenvectors; 6 signals: R, G, B without filter and with Wratten absorption filter number 38; (original -> reproduction).

Figure 35 and Figure 36 show, respectively, the spectral rms error factor, and the ΔE^*_{94} histogram for the spectral reconstruction using 6 eigenvectors; 6 signals: R, G, B without filter and with Wratten absorption filter number 38.

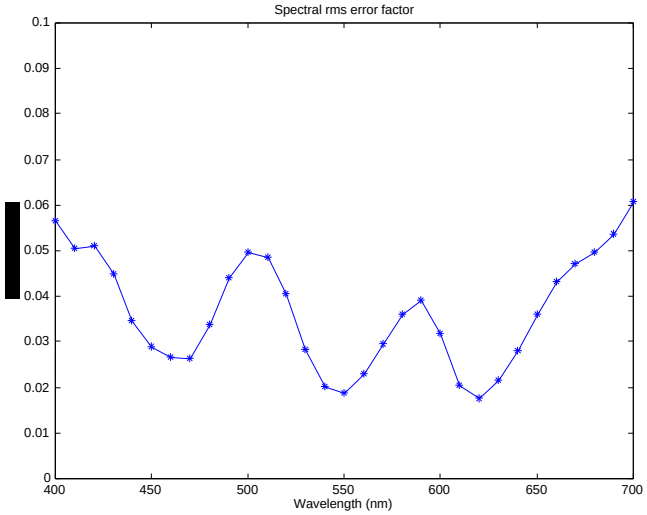


Figure 35. Spectral rms error for spectral reconstruction using 6 eigenvectors; 6 signals: R, G, B without filter and R, G, B with Wratten absorption filter number 38.

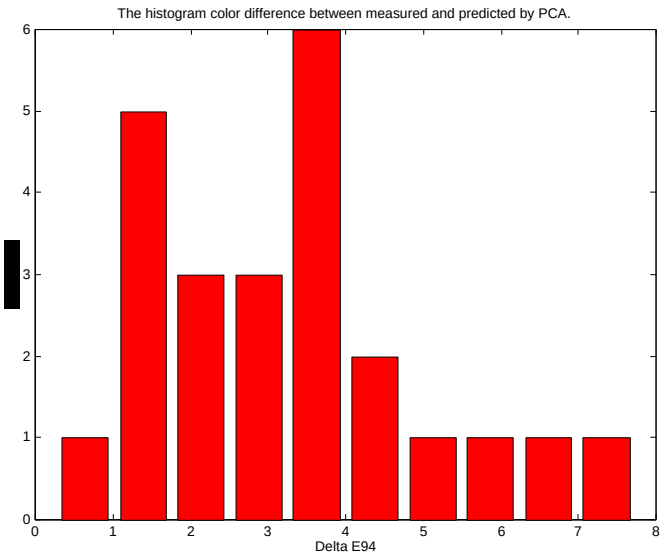


Figure 36. ΔE^*_{94} histogram for spectral reconstruction using 6 eigenvectors; 6 signals: R, G, B without filter and R, G, B with Wratten absorption filter number 38.

The colorimetric and spectral performance of the spectral reflectance in reflectance space for the Sony digital still camera was, as expected, worse than the result produced using IBM Pro\3000 digital camera system in the reproduction of Macbeth ColorChecker using measured digital counts.